AI in Space:
From Earth Orbit to Mars and Beyond!

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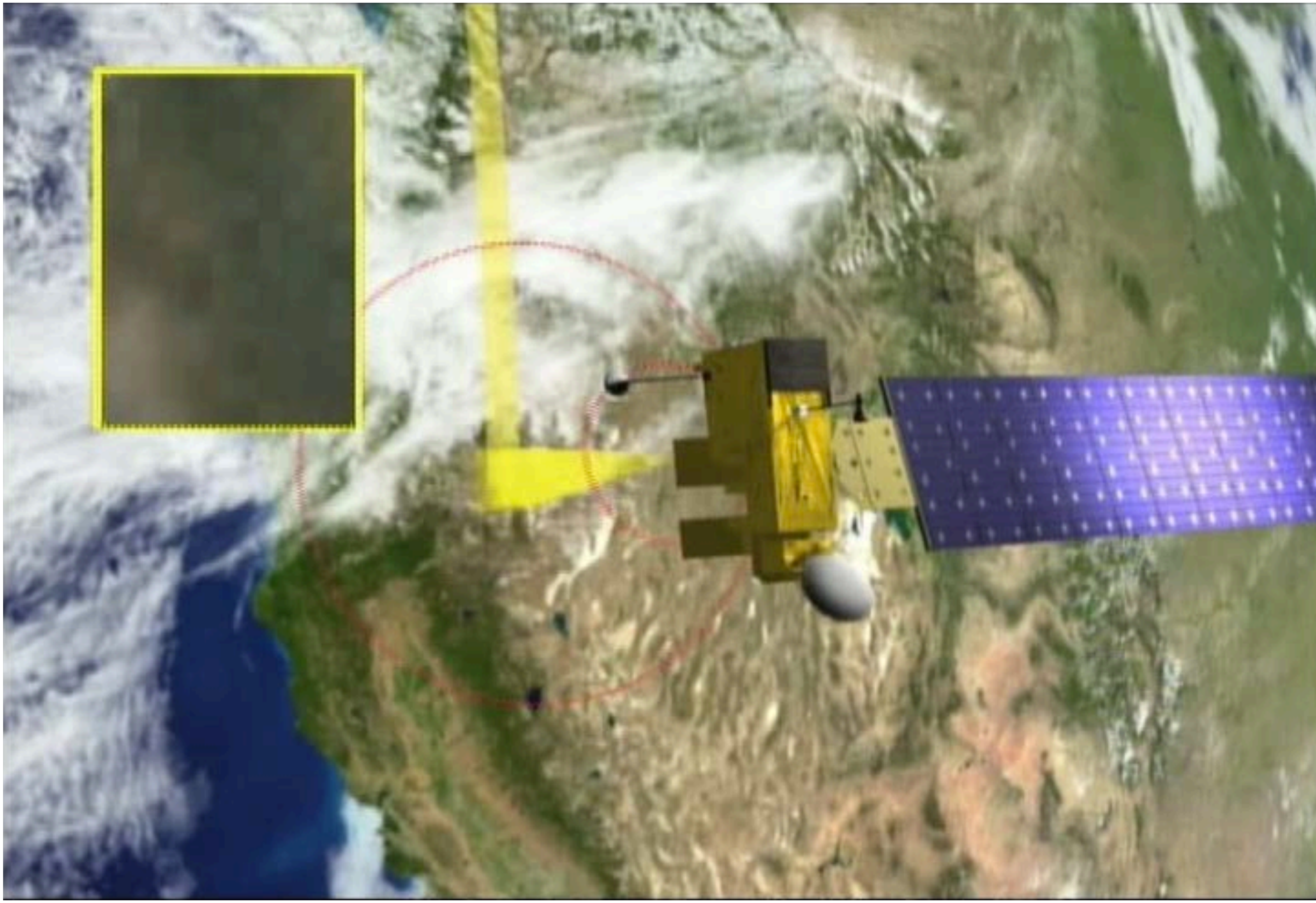
JPL Clearance:: CL 21-0532.

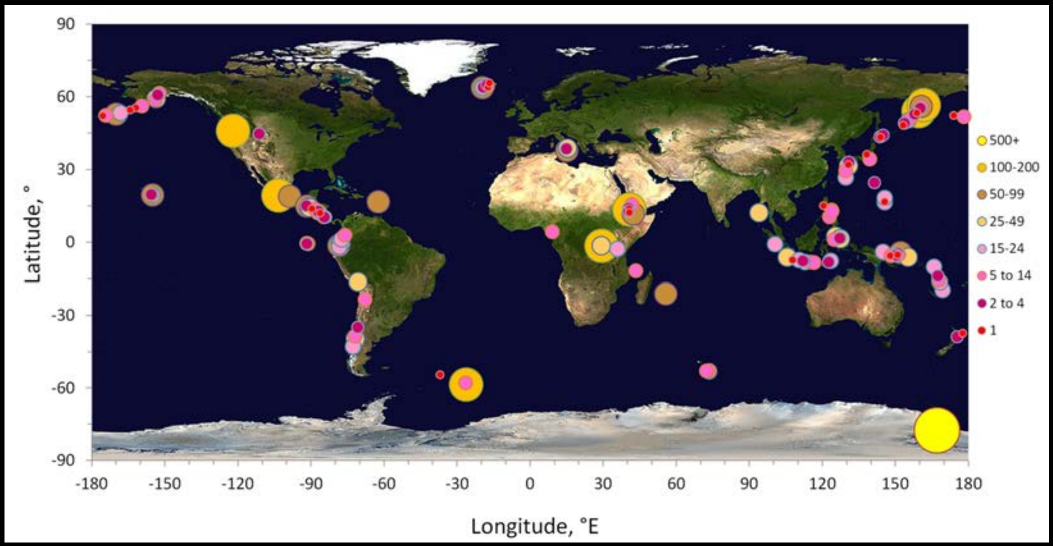

In 2004, AI in Space becomes a reality
Autonomous Sciencecraft AI Software operates the EO-1 spacecraft for over a dozen years, acquiring over 60,000 images, issuing almost $3 million commands



Simultaneously the Earth Observing Sensorweb links together scores of spacecraft, ground observatories, and air and marine assets to monitor volcanos, flooding, wildfires and more, acquiring thousands of images without any human intervention!

Example: NASA ASE/EO-1 Volcanoes

- Automated tasking: Volcano Sensorweb
  - Links together scores of space, ground, other assets
  - Automated Data analysis, triage to generate prioritized requests → ASE/EO-1 service → products delivered to stakeholders.
  - Over 100,000 alerts/triggers
    End Result, - Thousands of volcanic scenes 2008-2017,
    35%+ of said scenes with thermal signatures!
    Compare to MODIS background < 1% of scenes with active thermal signature.



Partners (incomplete list):
MODVOLC
GOESVOLC
AFWA
VAAC
Iceland/MEVO
Etna VO (U. Firenze)
MEVO (NM Tech)
HVO (Kilauea)
IEGPN (Ecuador)
CVO (Mount St. Helens)

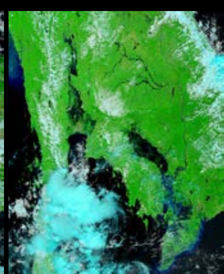
See [Chien et al. 2005 IEEE IS, Davies et al. 2006 EOS, Davies et al. 2005, 2007, 2016a,b]

Example: NASA ASE/EO-1 Flooding

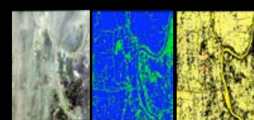
- Automated tasking: Thailand Flood Sensorweb
  - Links together space, ground assets
  - Automated Data analysis, triage to generate prioritized requests
    - → ASE/EO-1observation service and others
    - → products to stakeholders
  - Fuse data from satellite, ground sensor, and model sources

+100% temporal coverage for 2010-2011, 2011-2012 Flooding Seasons

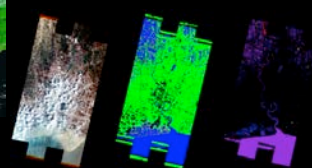
Dry: March 6, 2011



Flooded: October 27, 2011

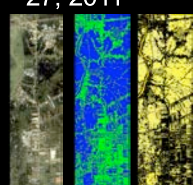


GeoEye-1

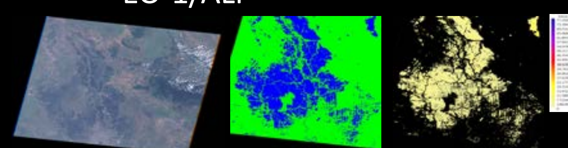


EO-1/ALI

In-situ data and Model



Ikonos



Landsat-7 ETM

Partners:
HAII (Thailand)
Digital Globe (Worldview)
Geo-Eye
Radarsat
Landsat
LANCE-MODIS

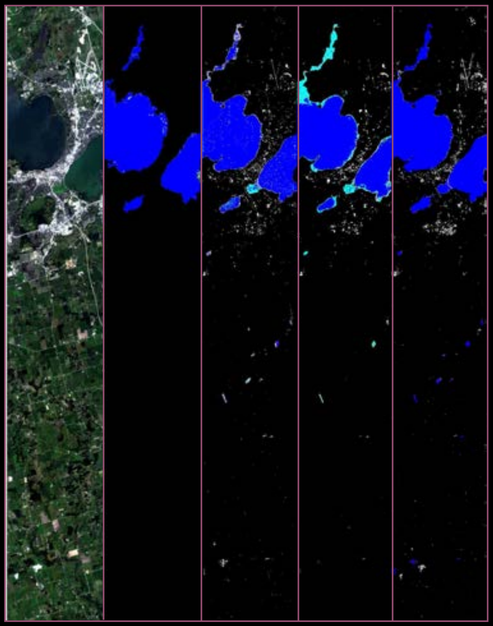
See [Chien et al. 2011 IGARSS, 2013 JSTARS]. See also Wildfires [Chien et al. 2011 JSTARS, Chien et al. JAIS 2018]

Land, Ice, Water, Snow Detection using Support Vector Machines

- Primary Purpose
  - Identify areas of land cover (land, ice, water, snow) in a scene
- Three algorithms:
  - Scientist manually derived
  - Automatic best ratio
  - Support Vector Machine (SVM)

Classifier	Expert Derived	Automated Ratio	SVM
cloud	45.7%	43.7%	58.5%
ice	60.1%	34.3%	80.4%
land	93.6%	94.7%	94.0%
snow	63.5%	90.4%	71.6%
water	84.2%	74.3%	89.1%
unclassified	45.7%		

Lake Mendota, Wisconsin

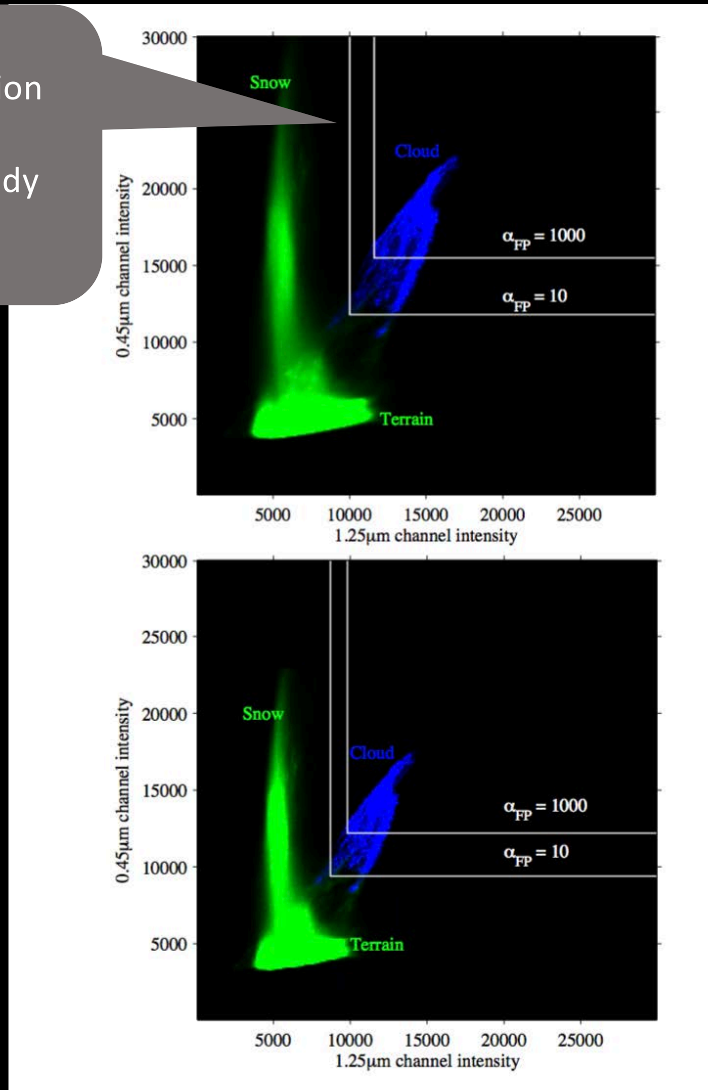


Visible Image | Expert Labeled | Expert Derived | Automated Ratio | SVM

T. Doggett et al. 2006 RSE

Bayesian Thresholding

Bayesian thresholding exploits the natural division between dark surface materials and bright cloudy regions at particular wavelengths.



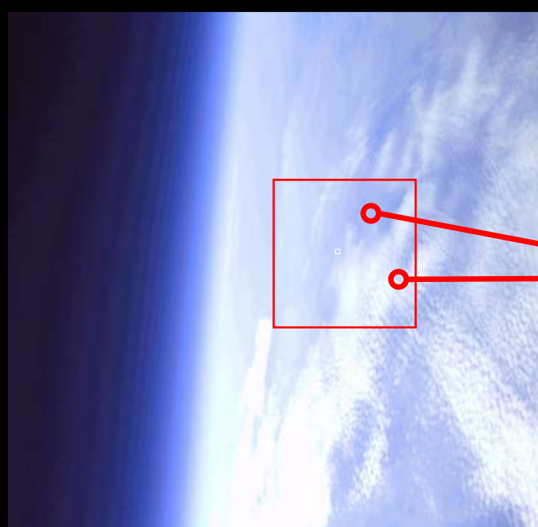
- While the RDF method examines a window of values around the pixel to be classified, BT classifies each pixel independently.
- BT was previously employed to analyze data collected by the AVIRIS-C airborne sensor (Thompson et al. 2014).
- For EO- 1, BT used Hyperion bands at 447, 1245, and 1658 nm to span the range from blue to short-wave infrared.

Image courtesy Thompson et al. 2014 TGARS

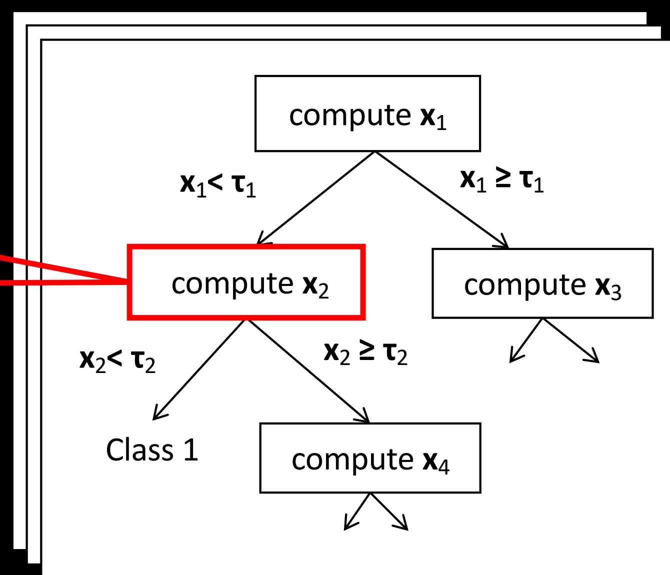
TextureCam – Random Decision Forests

Pixel classification for cloud screening,

Pixel to be classified

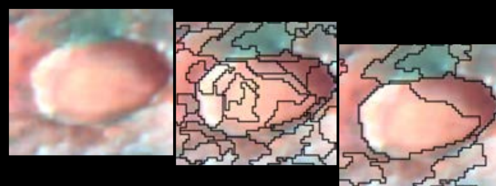


Random forest classifier



[Thompson et al., i-SAIRAS 2012; Wagstaff et al., *GRL* 2013; Bekker et al., *Astrobiology* 2014]

Onboard Hyperspectral Analysis



Superpixel segmentation
+
The sequential maximum angle convex cone (SMACC)
endmember extraction

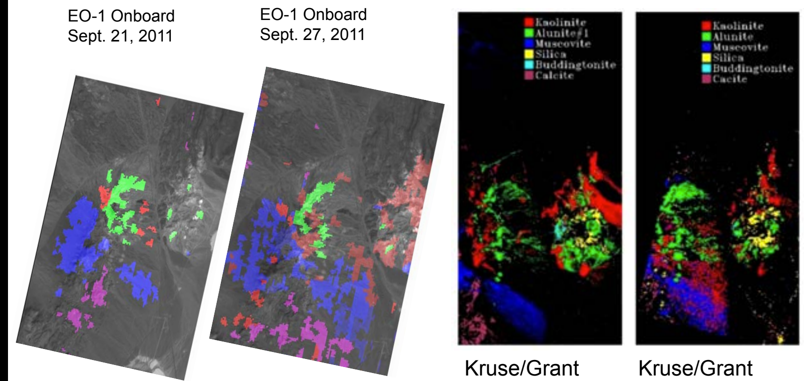
Results from onboard EO-1 (9/2011)

D. Thompson et al. 2012 TGARS

Repeatability: maps

EO-1 Onboard Sept. 21, 2011

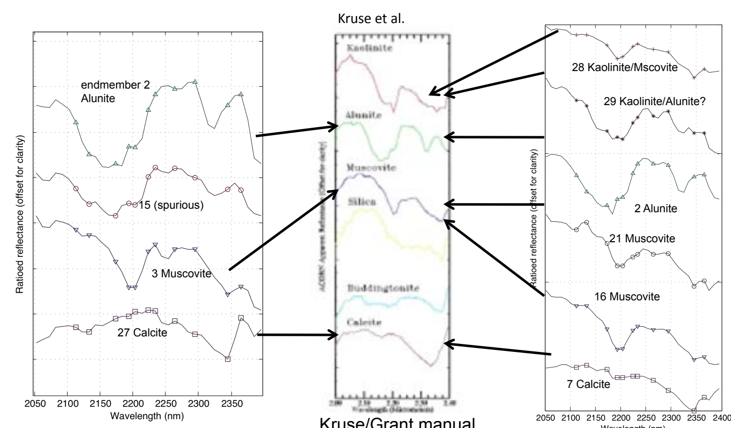
EO-1 Onboard Sept. 27, 2011



Kruse/Grant manual analysis (AVIRIS)

Kruse/Grant manual analysis (Hyperion)

Repeatability: detections

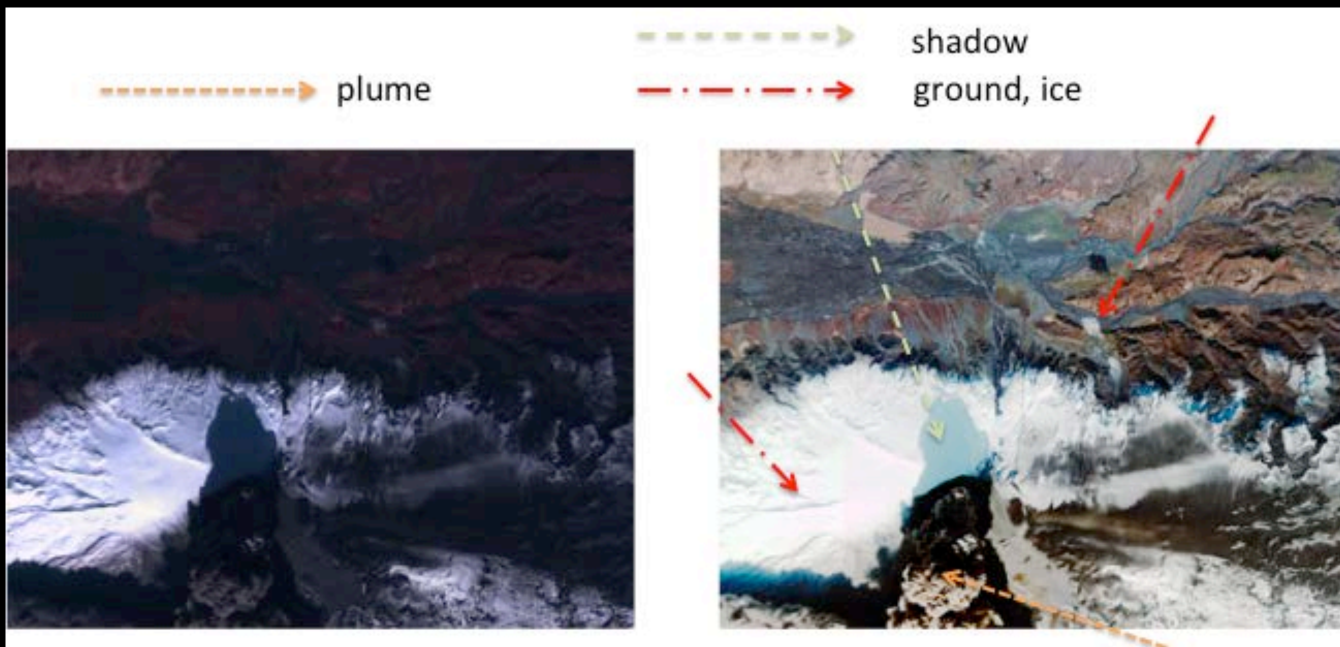


EO-1 Onboard Sept. 21, 2011

Kruse/Grant manual analysis (Hyperion)

EO-1 Onboard Sept. 27, 2011

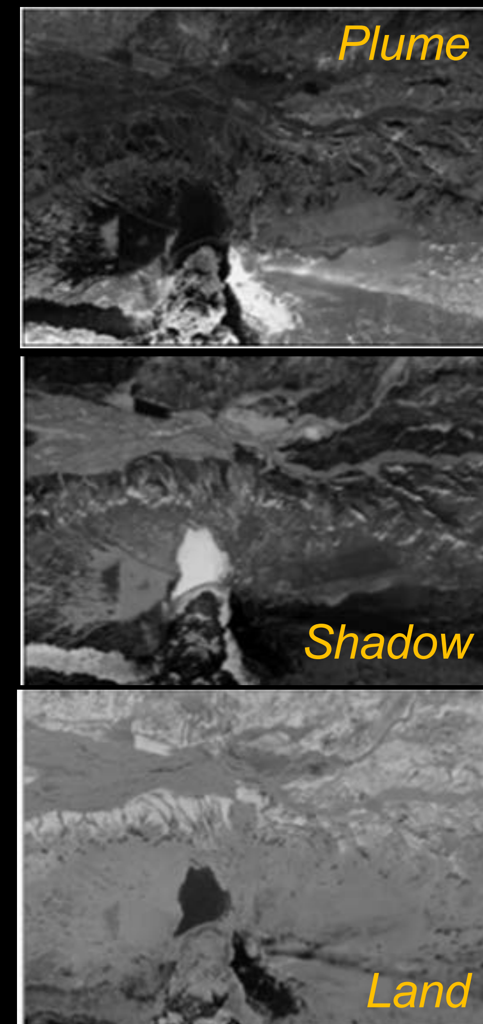
WorldView-2 Data



WorldView-2 Image of Eyjafjallajökull eruption, acquired April 17, 2010

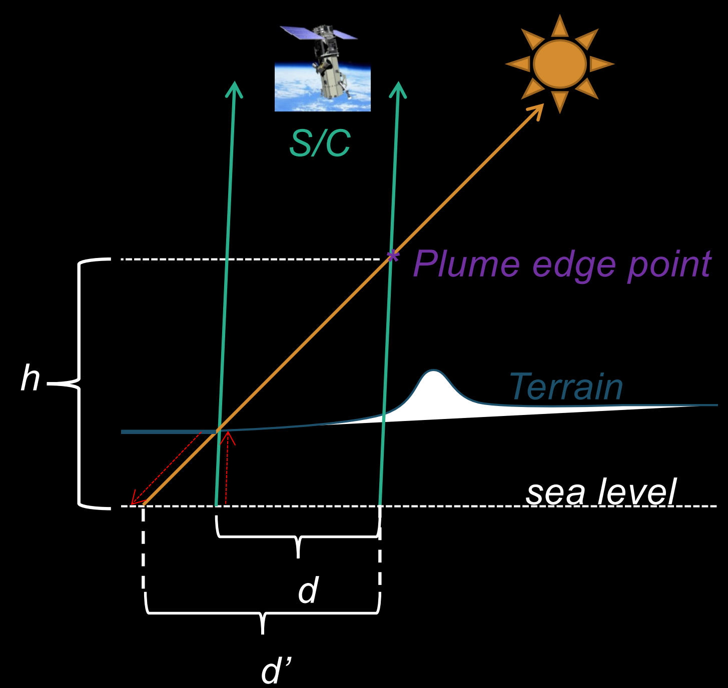
Histogram-equalized image

Mclaren et al. 2012, SPIE



Height Estimation

- Estimate plume height from shadows
- Followed calculations derived in A. J. Prata and I. F. Grant, “Determination of mass loadings and plume heights of volcanic ash clouds from satellite data”
- Rotated classification maps so sun rays are coming from –Y axis (bottom of the image)
- Collected shadow line segments which have a neighboring plume region in sunward direction
- Corrected shadow lengths for:
  - Sun and spacecraft azimuth, elevation
  - Ground elevation at shadow edge
    - ASTER GDEM2 DEM
    - 30m horiz. spacing, 1m vert.



d *: Initial shadow length*
d’*: Shadow length after projecting up to DEM & down along sun vector*
h *: Plume point height*

Salience – Unsupervised Novelty Detection

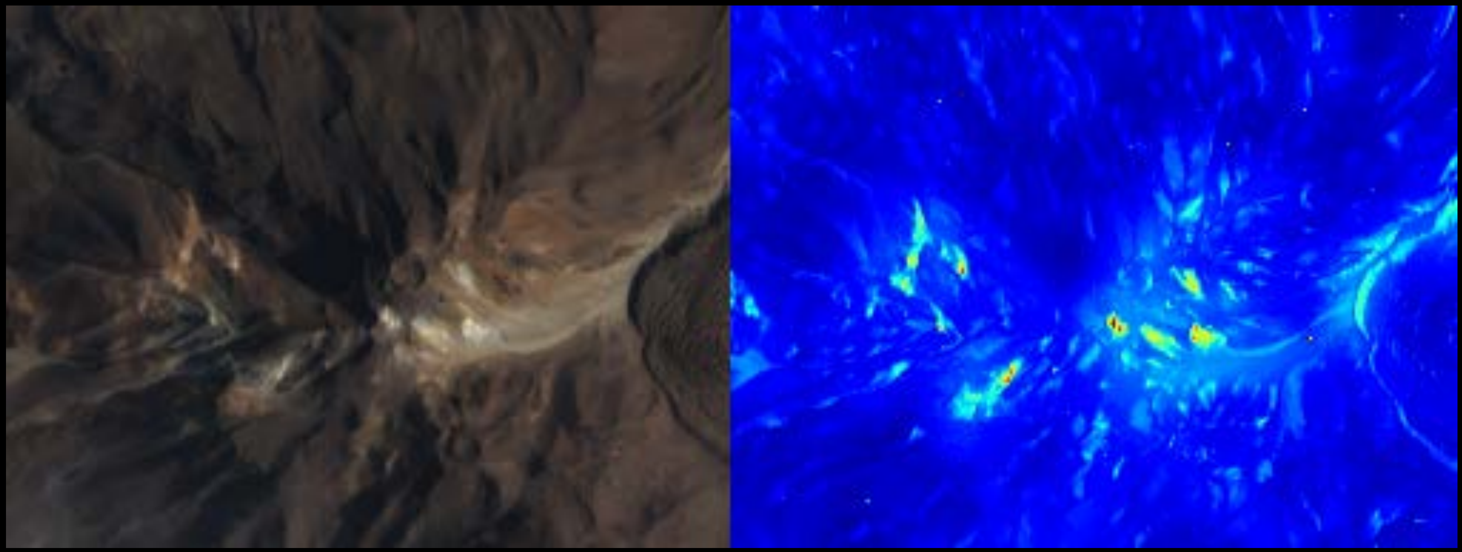
- Salience is an unsupervised algorithm that assigns a score to each pixel that captures how anomalous it is within its local context. The salience S of pixel p is computed with respect to the histogram P_w of intensity values in the surrounding window w:

$$S(p, w) = \frac{1}{M} \sum_i |p - i| P_w(i)$$

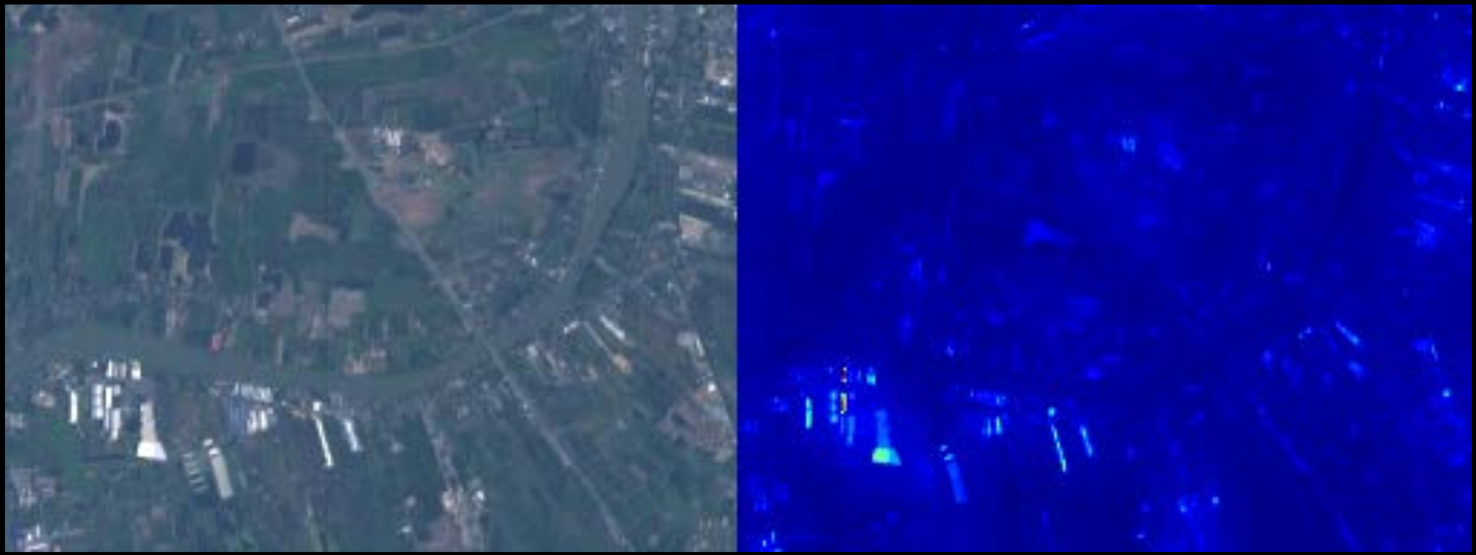
- where M is a normalization factor that is the maximum
- salience possible given the window histogram and size:

$$M = N(N-1) \sum_i P_w(i)$$

Salience for Volcano in Chile

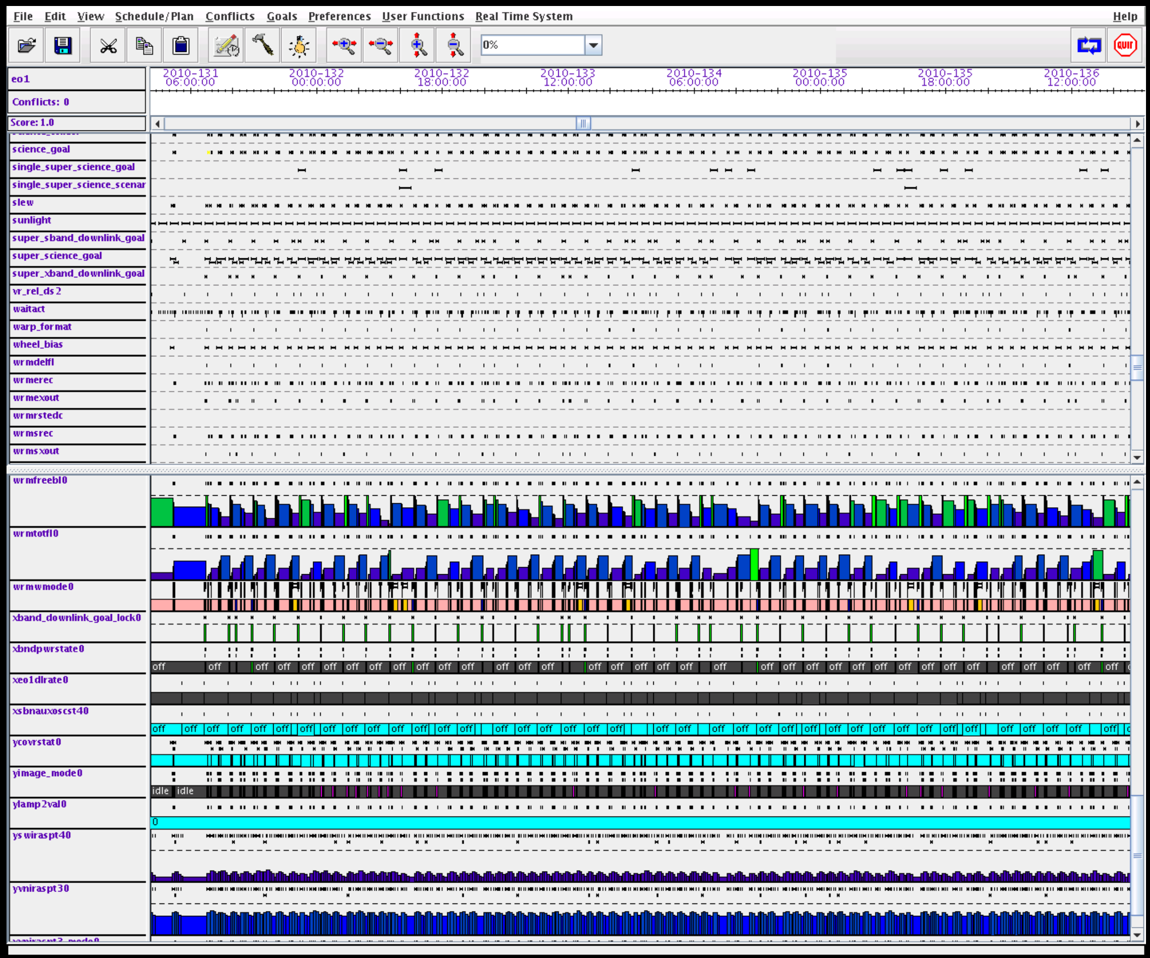


Salience for buildings in Thailand



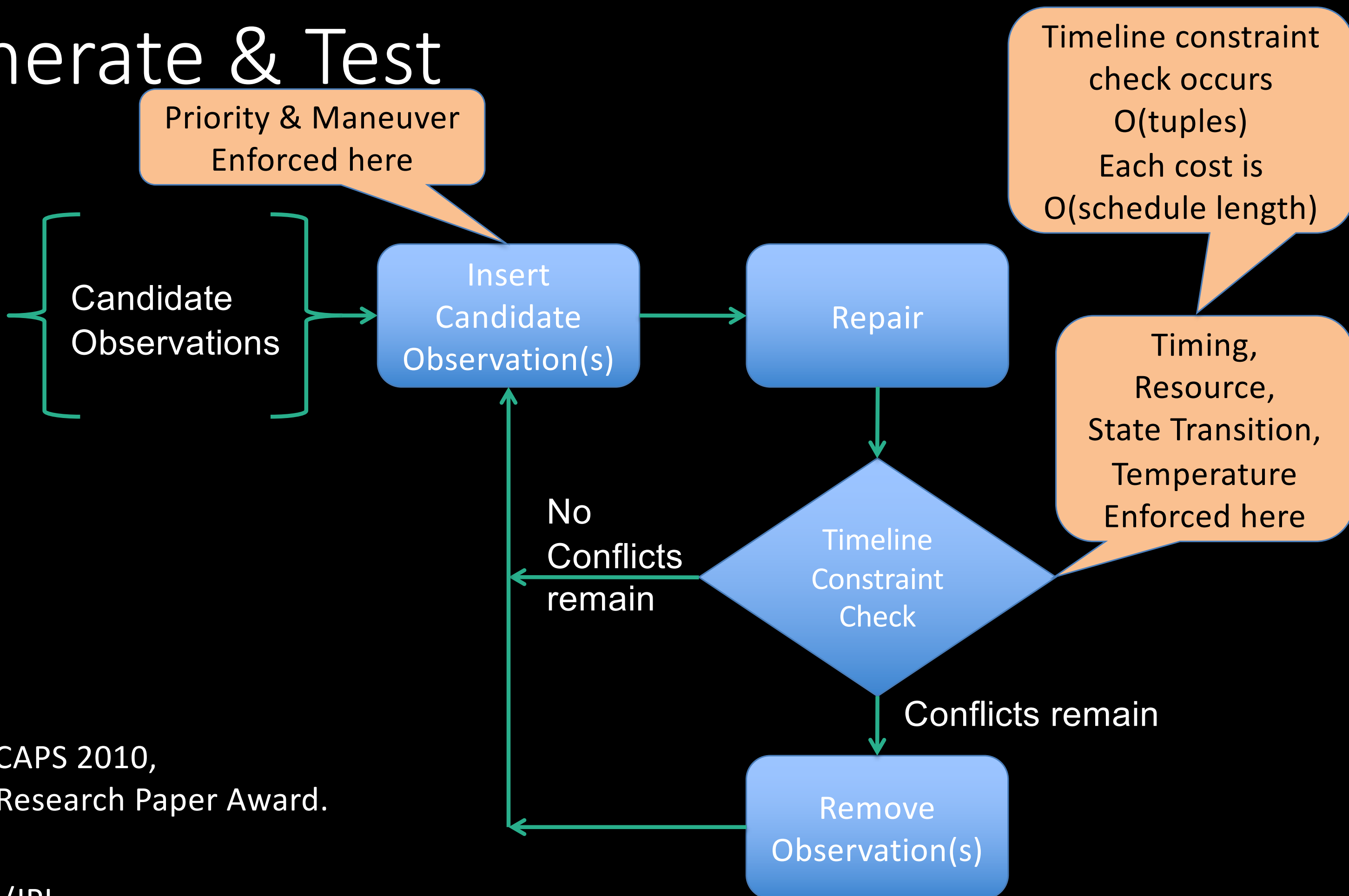
Wagstaff et al. 2018 i-sairas

Timeline-based Scheduling



Many timeline based schedulers in use for space missions.
See
[Chien et al. 2012, SpaceOps]

Generate & Test



See:
Chien et al., ICAPS 2010,
Best Applied Research Paper Award.

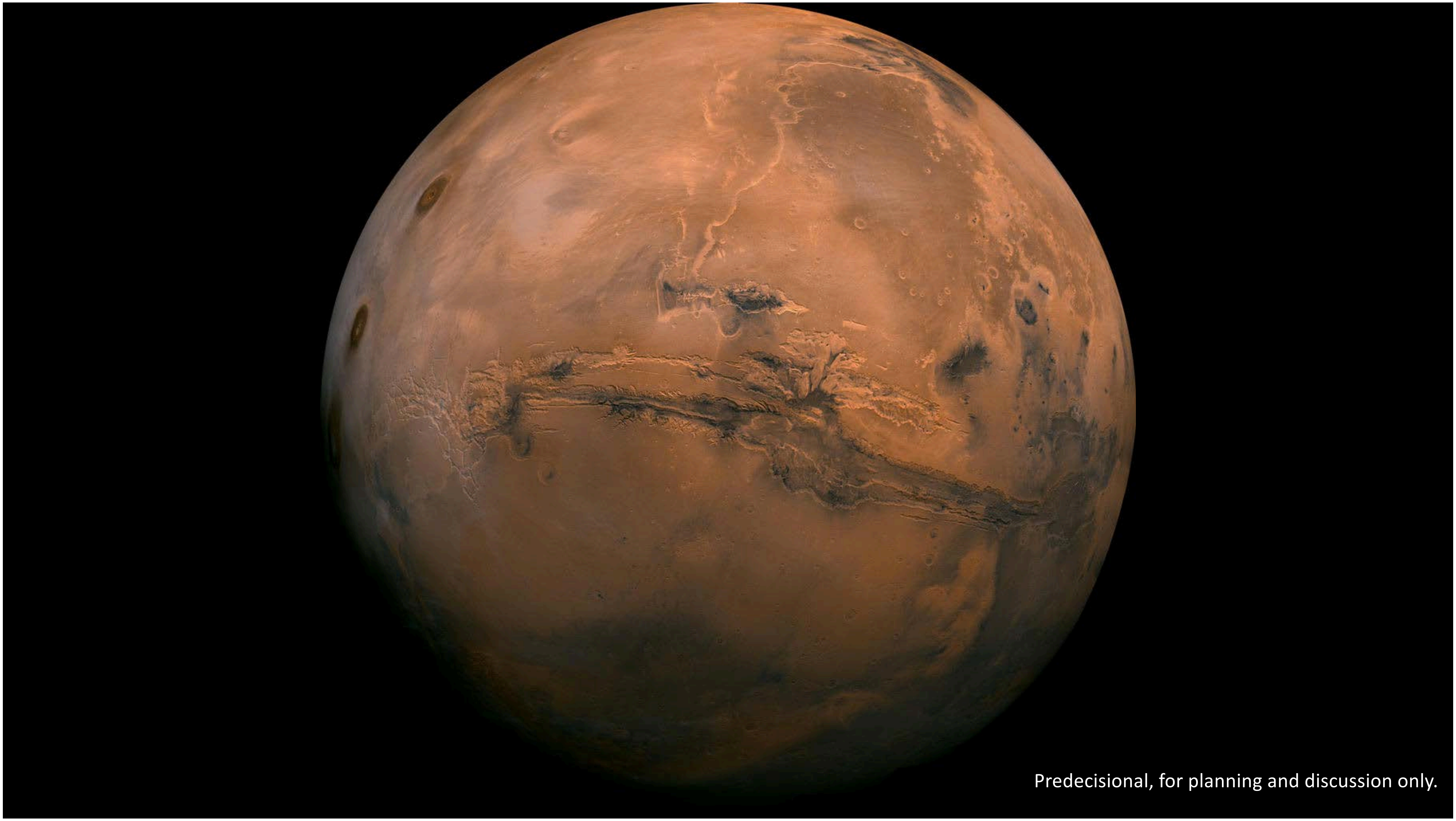
POC: S. Chien/JPL

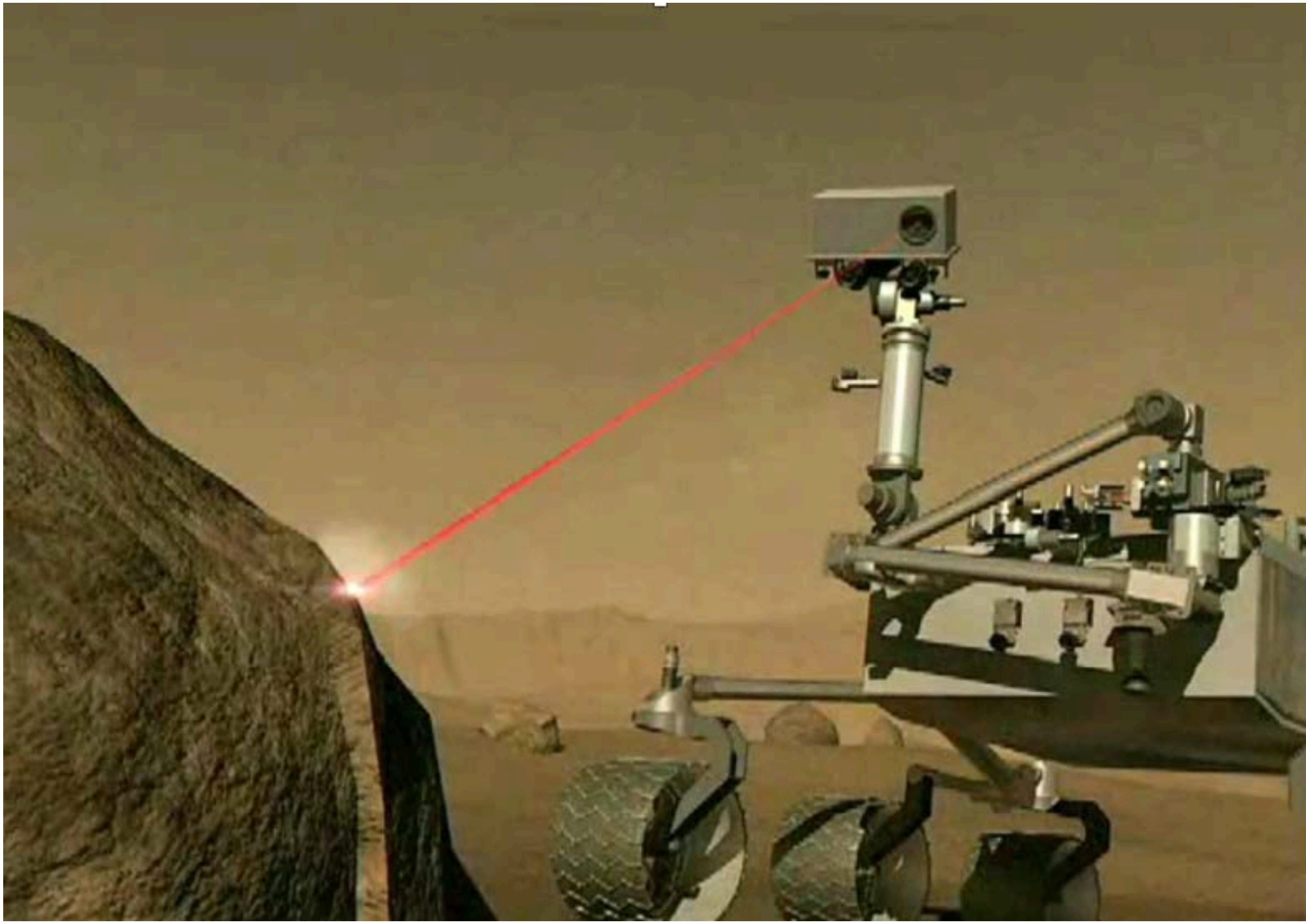
WIRED

The Journey of NASA's Smartest Satellite Finally Comes to an End

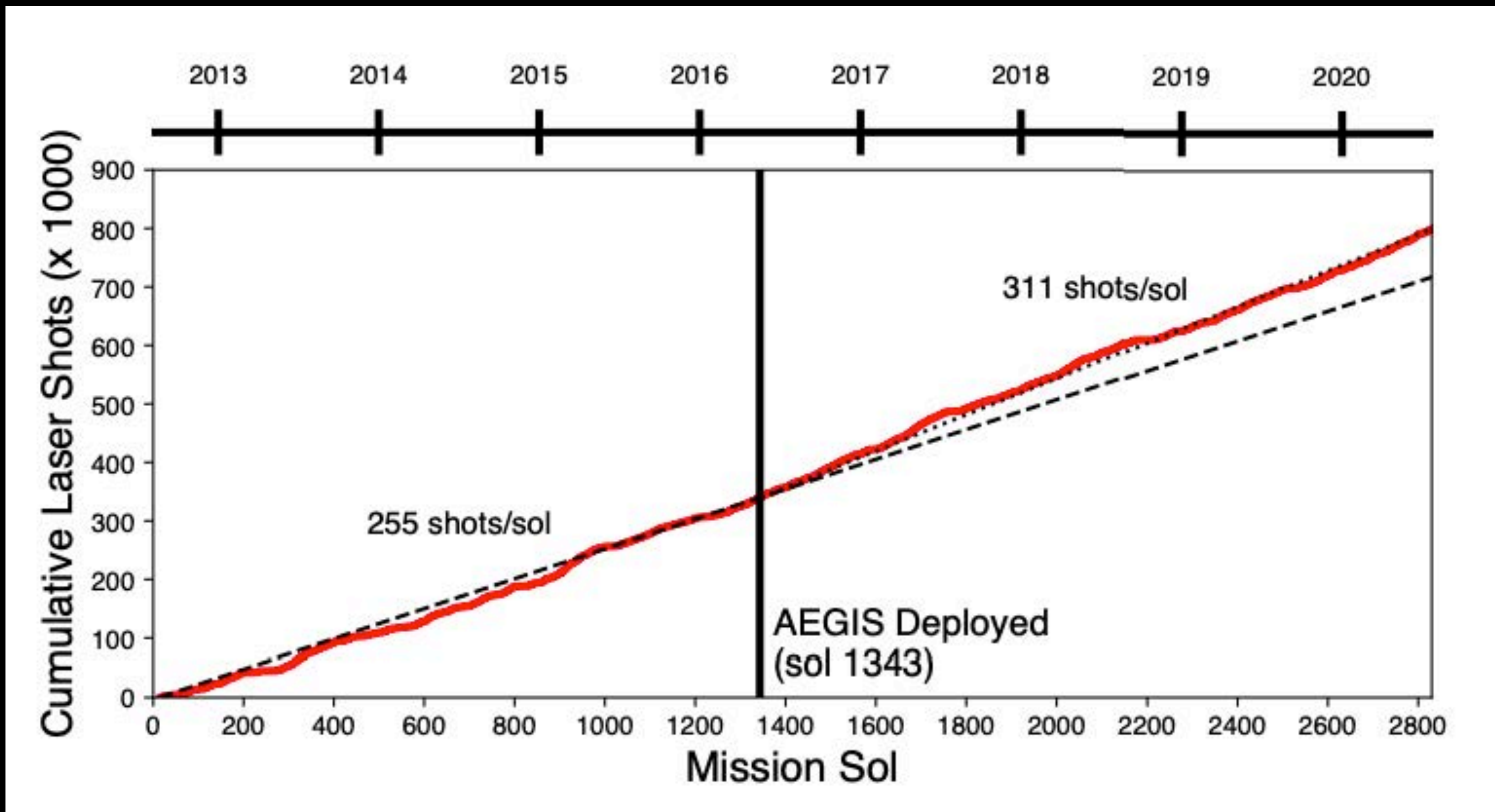
Manam Volcano viewed from EO-1 on June 28th 2010 ALAMY

https://www.wired.com/2017/03/say-farewell-eo-1-nasas-smartest-satellite/

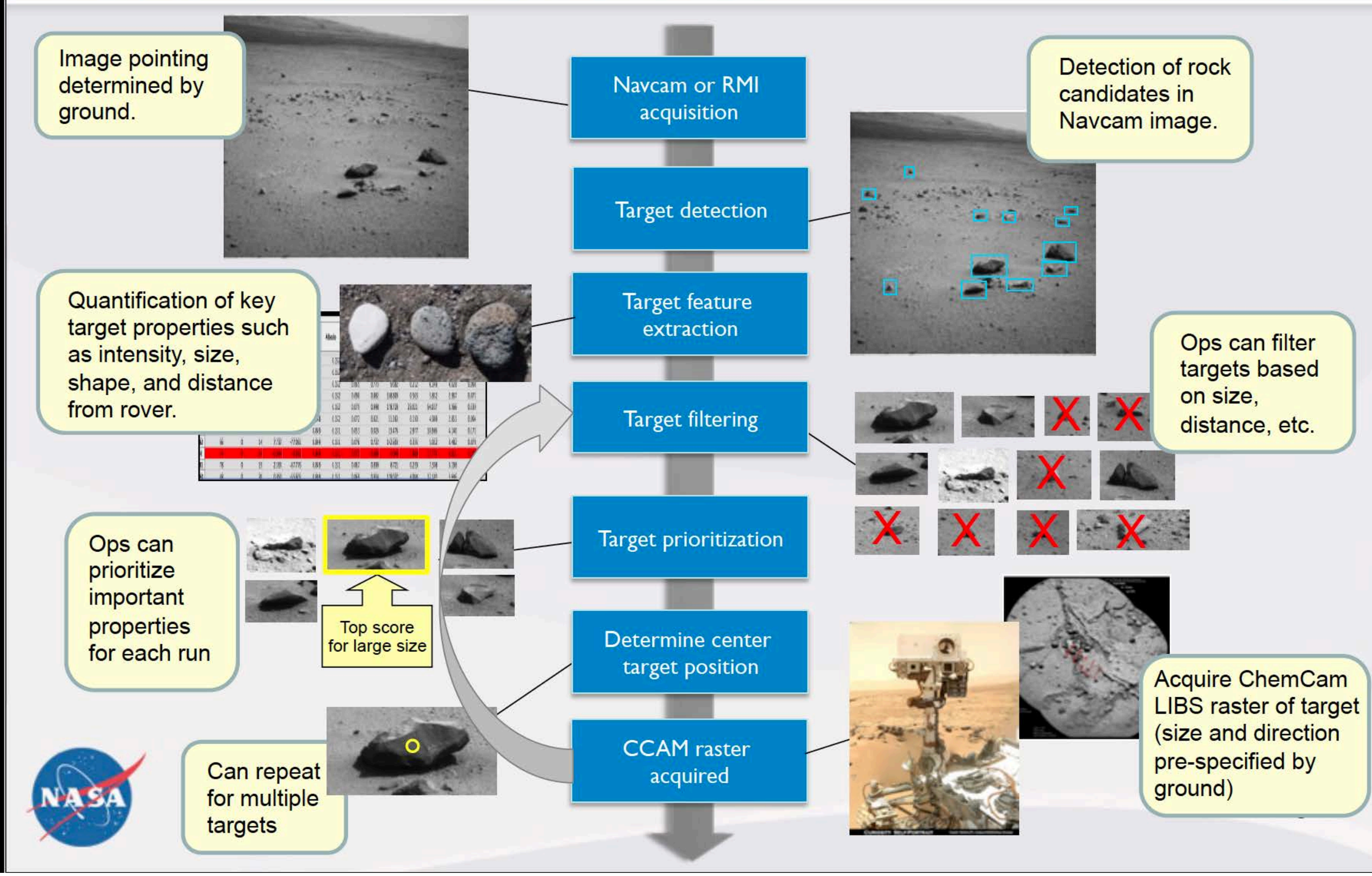

Predecisional, for planning and discussion only.

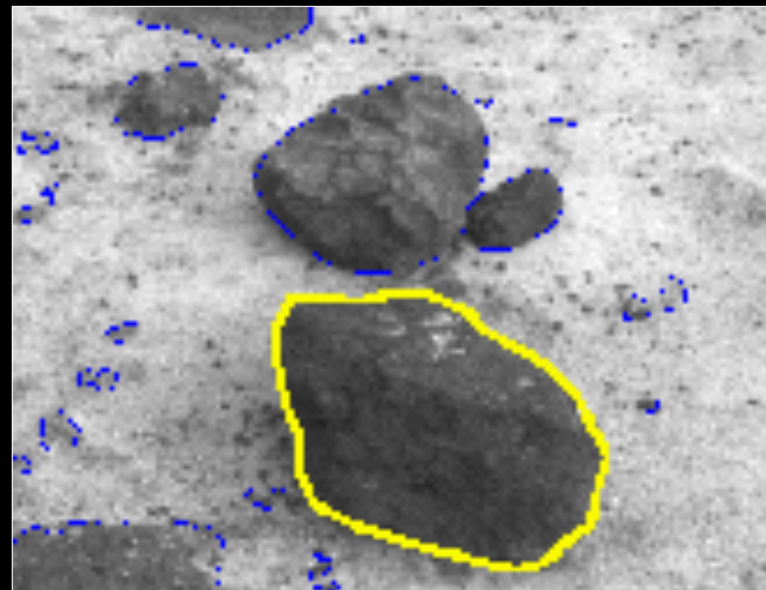


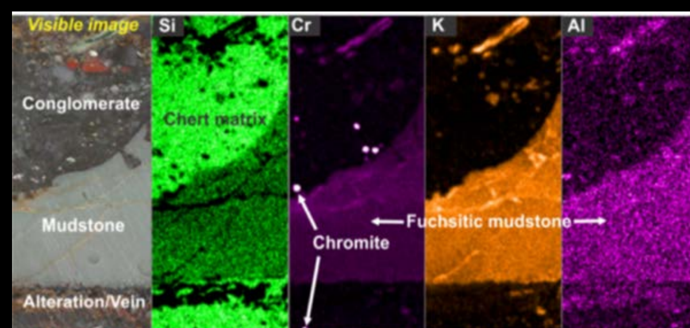
AI-based Targeting of the Chemcam laser on the Mars Science Laboratory Rover


2013
2014
2015
2016
2017
2018
2019
2020
Cumulative Laser Shots (x 1000)
900
800
700
600
500
400
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Mission Sol
255 shots/sol
311 shots/sol
AEGIS Deployed
(sol 1343)

Onboard Process for MSL

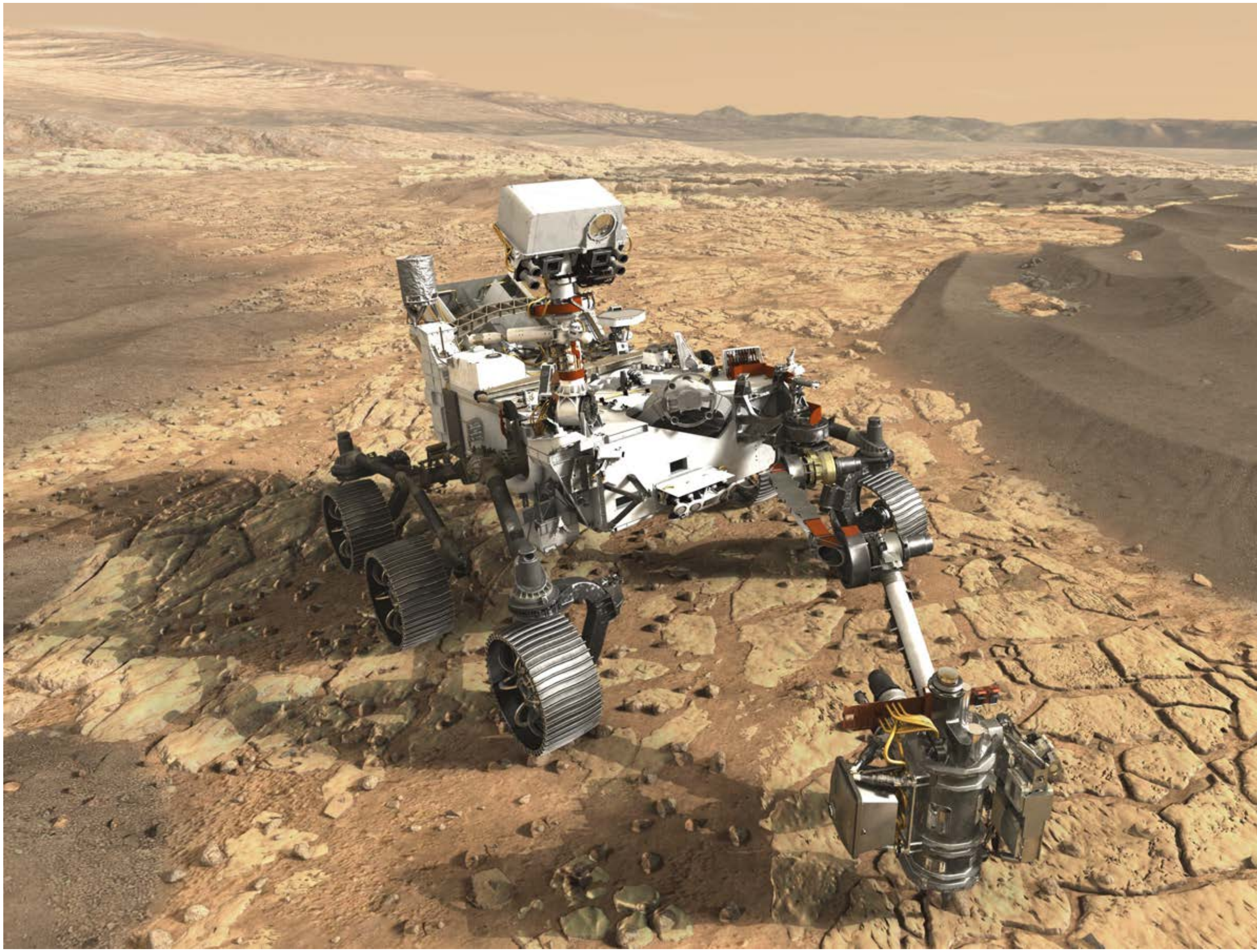






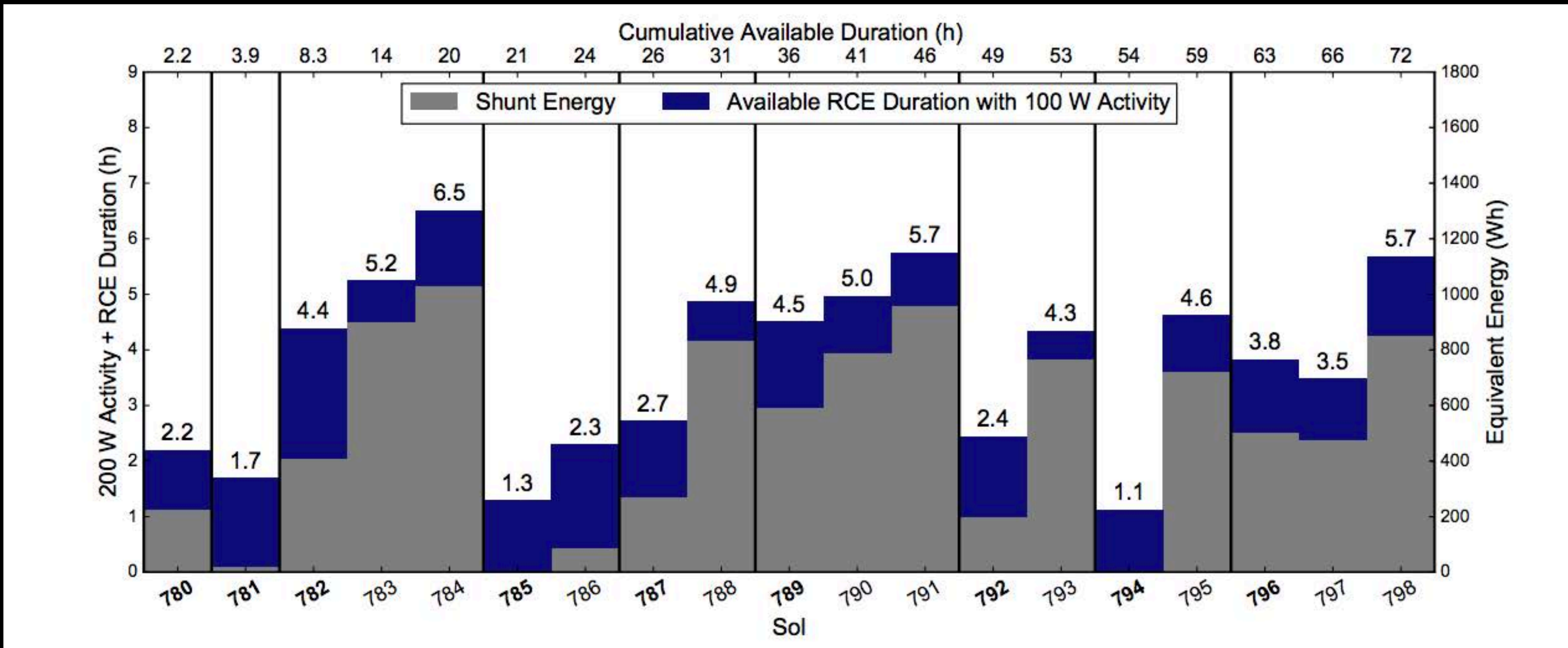
POC: T. Estlin, R. Francis/JPL
AEGIS/MER, winner of the 2011 NASA Software of the Year Award

Predecisional, for planning and discussion only.



Predecisional, for planning and discussion only.

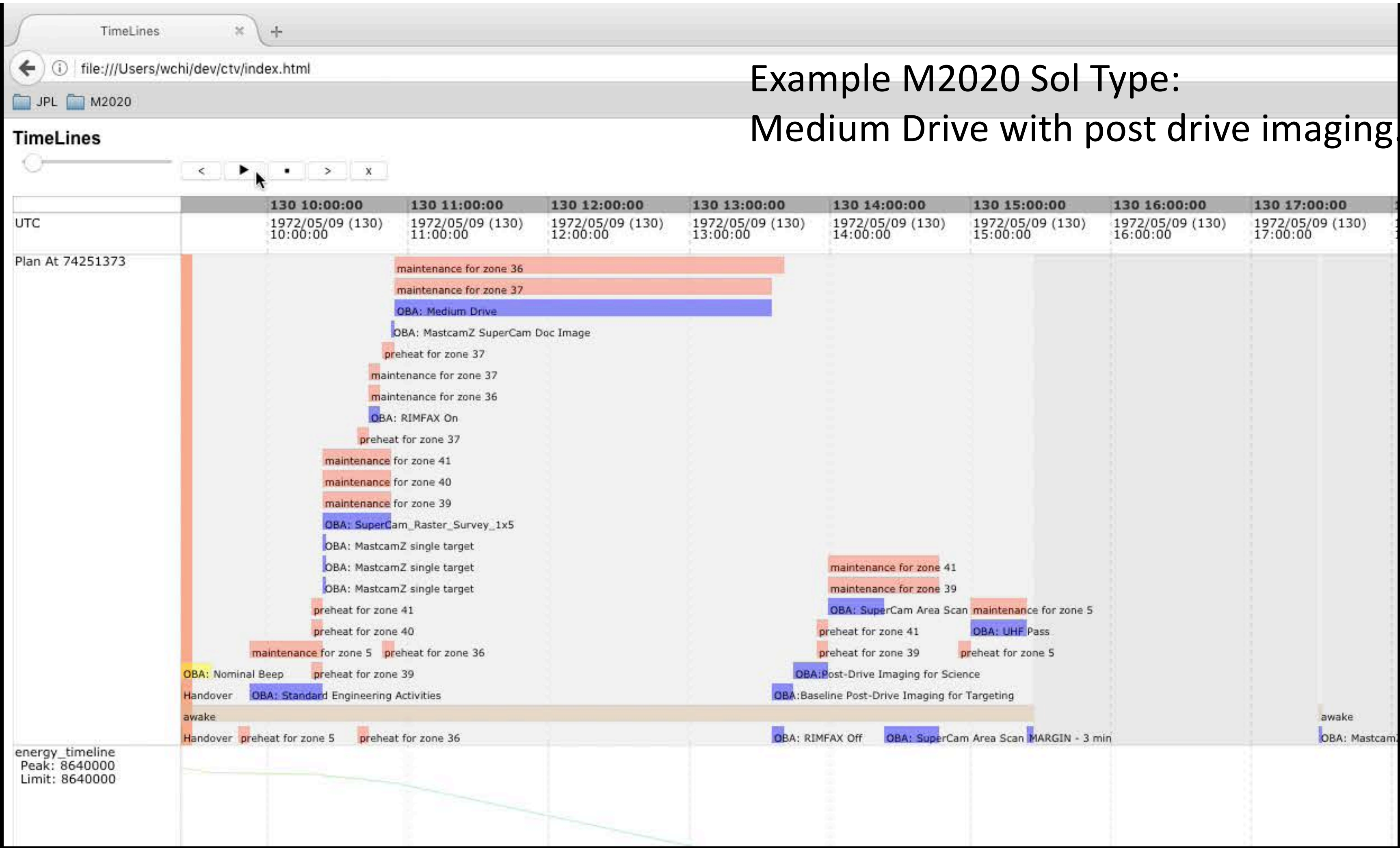
MSL unused Time/Energy



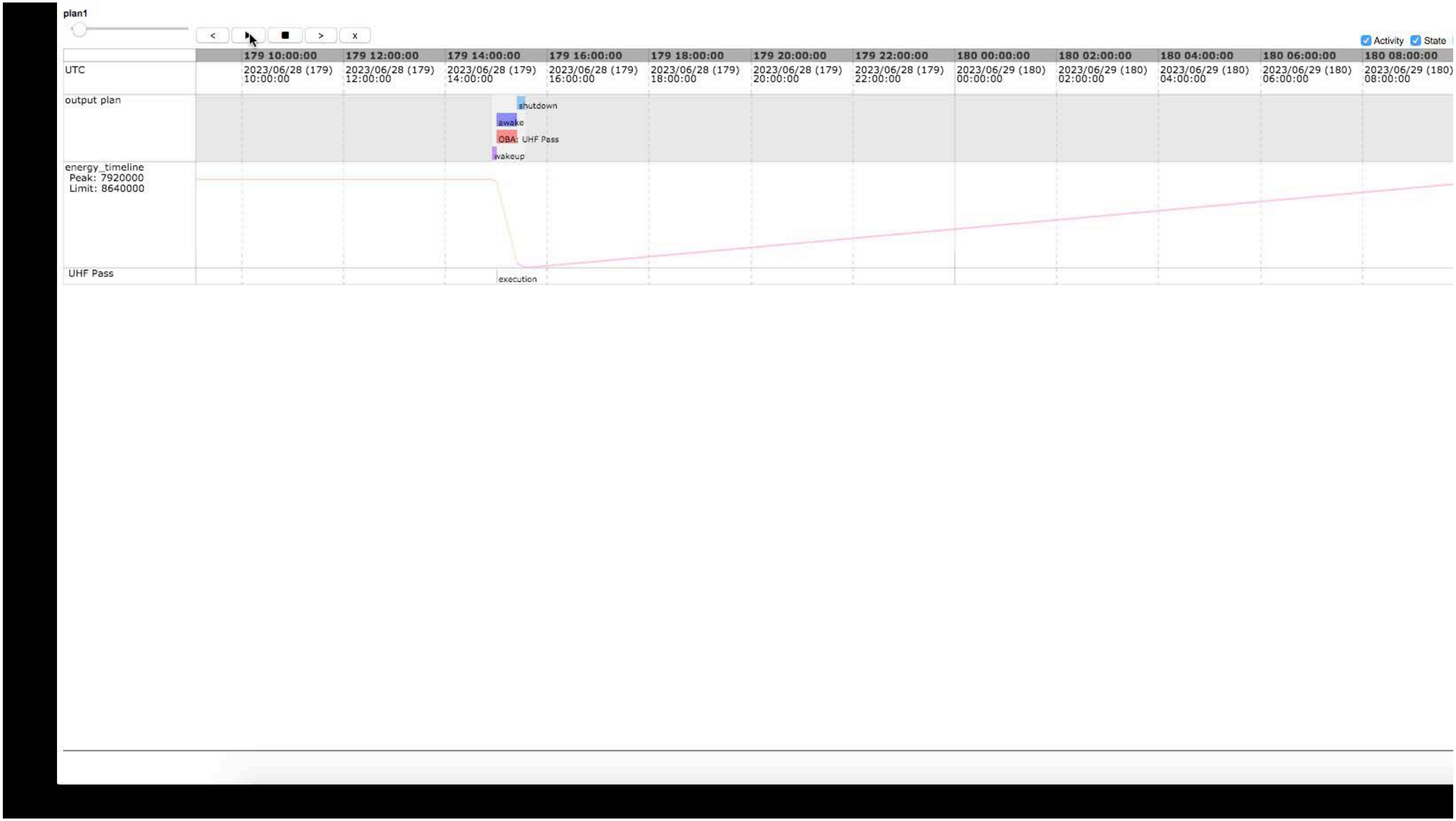
MSL submasters on average execution time 28% less than planned time (+ cleanups)

JPL

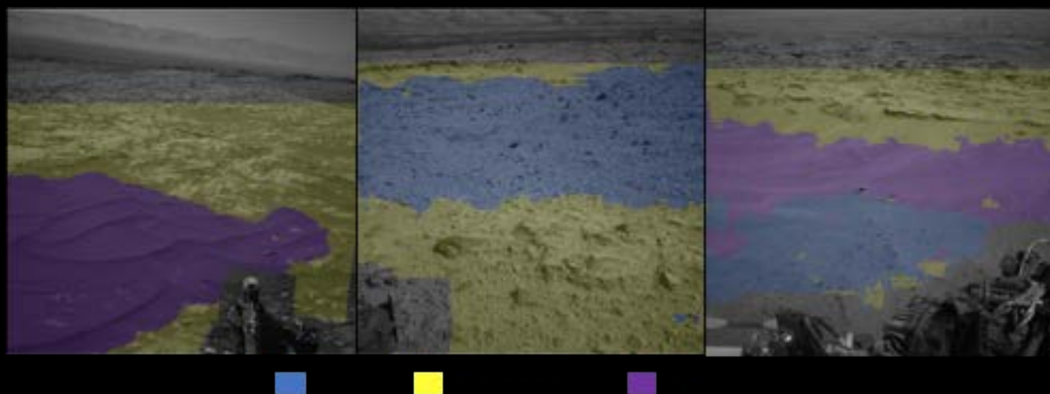
Example M2020 Sol Type:
Medium Drive with post drive imaging.



Rabideau et al. 2017 IWPSS; Chi et al 2018 ICAPS; Chi et al. 2019 ICAPS POC: S. Chien/JPL


plan1
Activity
State
179 10:00:00
179 12:00:00
179 14:00:00
179 16:00:00
179 18:00:00
179 20:00:00
179 22:00:00
180 00:00:00
180 02:00:00
180 04:00:00
180 06:00:00
180 08:00:00
UTC
2023/06/28 (179) 10:00:00
2023/06/28 (179) 12:00:00
2023/06/28 (179) 14:00:00
2023/06/28 (179) 16:00:00
2023/06/28 (179) 18:00:00
2023/06/28 (179) 20:00:00
2023/06/28 (179) 22:00:00
2023/06/29 (180) 00:00:00
2023/06/29 (180) 02:00:00
2023/06/29 (180) 04:00:00
2023/06/29 (180) 06:00:00
2023/06/29 (180) 08:00:00
output plan
shutdown
awake
OBA: UHF Pass
wakeup
energy_timeline
Peak: 7920000
Limit: 8640000
UHF Pass
execution

Future AI
Self Reliant Rover demonstrated an 80% reduction in time to complete a walkabout campaign [Gaines et al. 2020] by using onboard science driven AI. Technologies also very relevant to “long drive” scenarios.



Automated terrain (slip) analysis assists ground-based MSL rover planners more quickly and accurately plan rover paths [Ono et al. 2020].

		Predicted			
		Soil	Bedrock	Sand	Big Rock
Actual	Soil	96.00	0.31	3.69	0
	Bedrock	6.15	90.87	2.54	0.44
	Sand	0.25	3.23	96.51	0.01
	Big Rock	11.67	0.03	5.48	82.83

Table 3: MSL *NAVCAM-Random* confusion matrix percentages calculated with respect to the 3 label agreement test set. Overall accuracy is 94.97%.

		Predicted			
		Soil	Bedrock	Sand	Big Rock
Actual	Soil	99.10	0.32	0.57	0.01
	Bedrock	3.64	94.90	0.37	1.09
	Sand	0.88	5.62	93.45	0.05
	Big Rock	6.76	0	0	93.24

Table 4: MSL *NAVCAM-Merged* confusion matrix percentages calculated with respect to the 3 label agreement test set. Overall accuracy is 96.67%

Future rover missions can use this technology onboard to enable more capable slip-aware autonomous driving [Gaines et al. 2020].

Rosetta

Philae Lander Delivery

Image courtesy MPI/OSIRIS, ESA/Rosetta

Lander Delivery

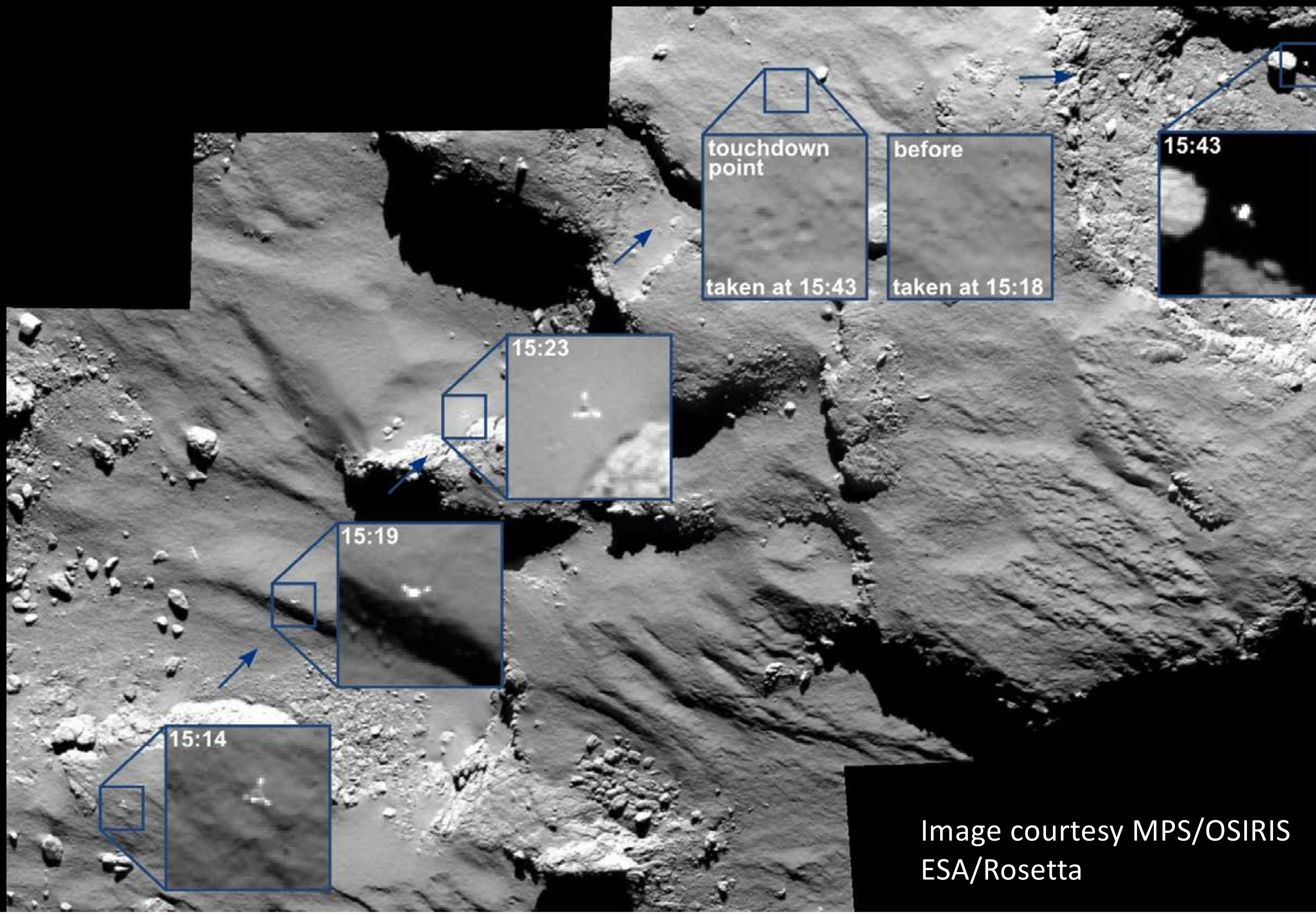
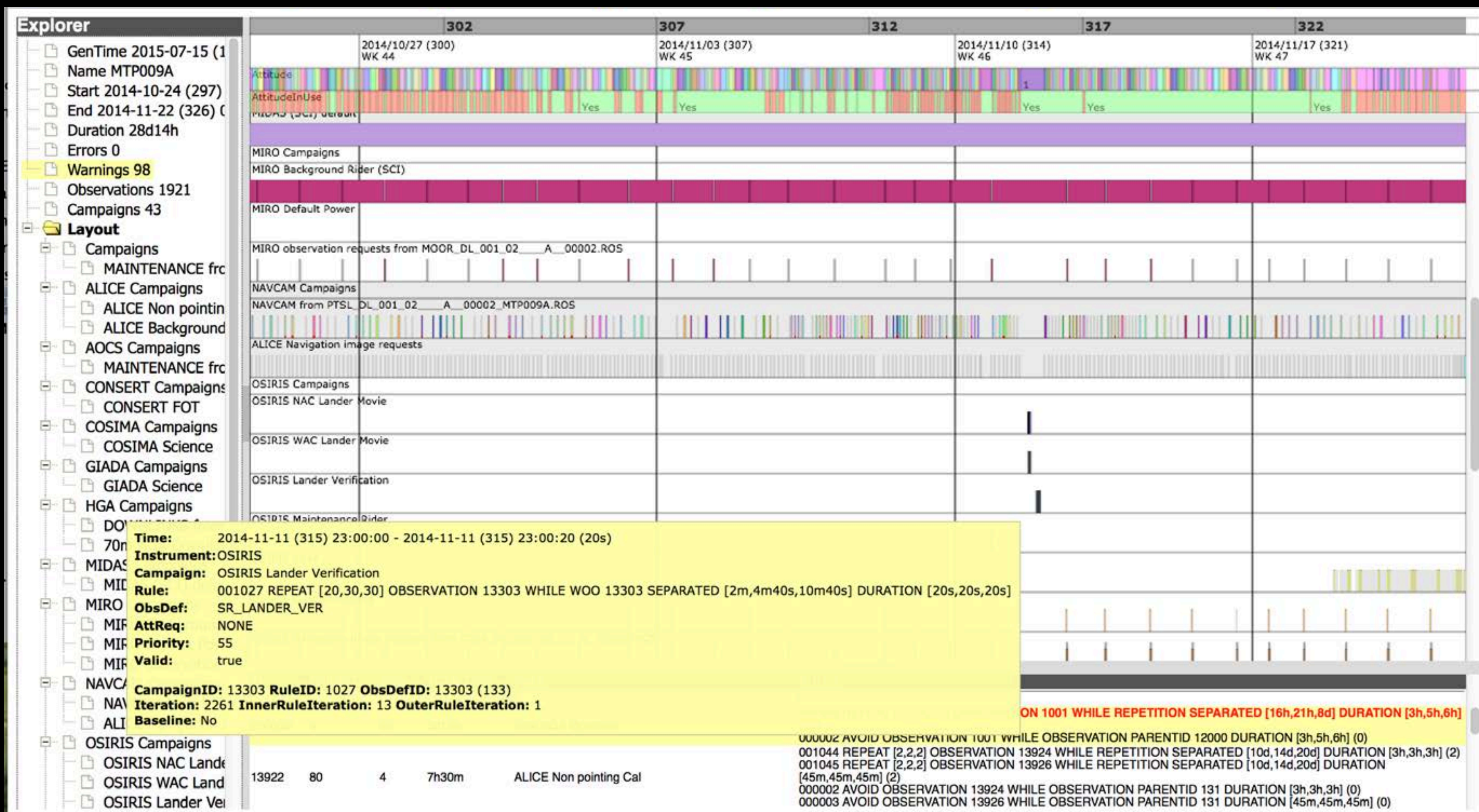
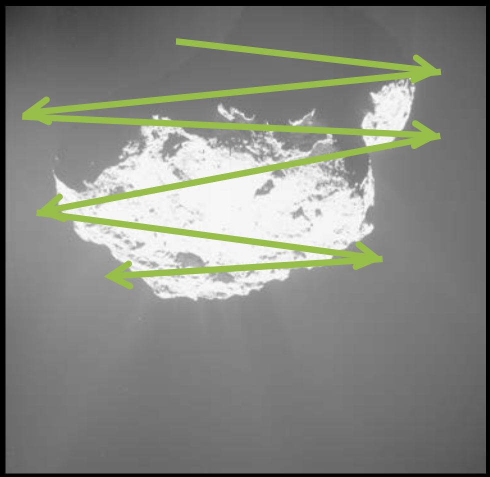


Image courtesy MPS/OSIRIS
ESA/Rosetta

Lander Delivery



Broad Sweeps vs Targeted Sweeps

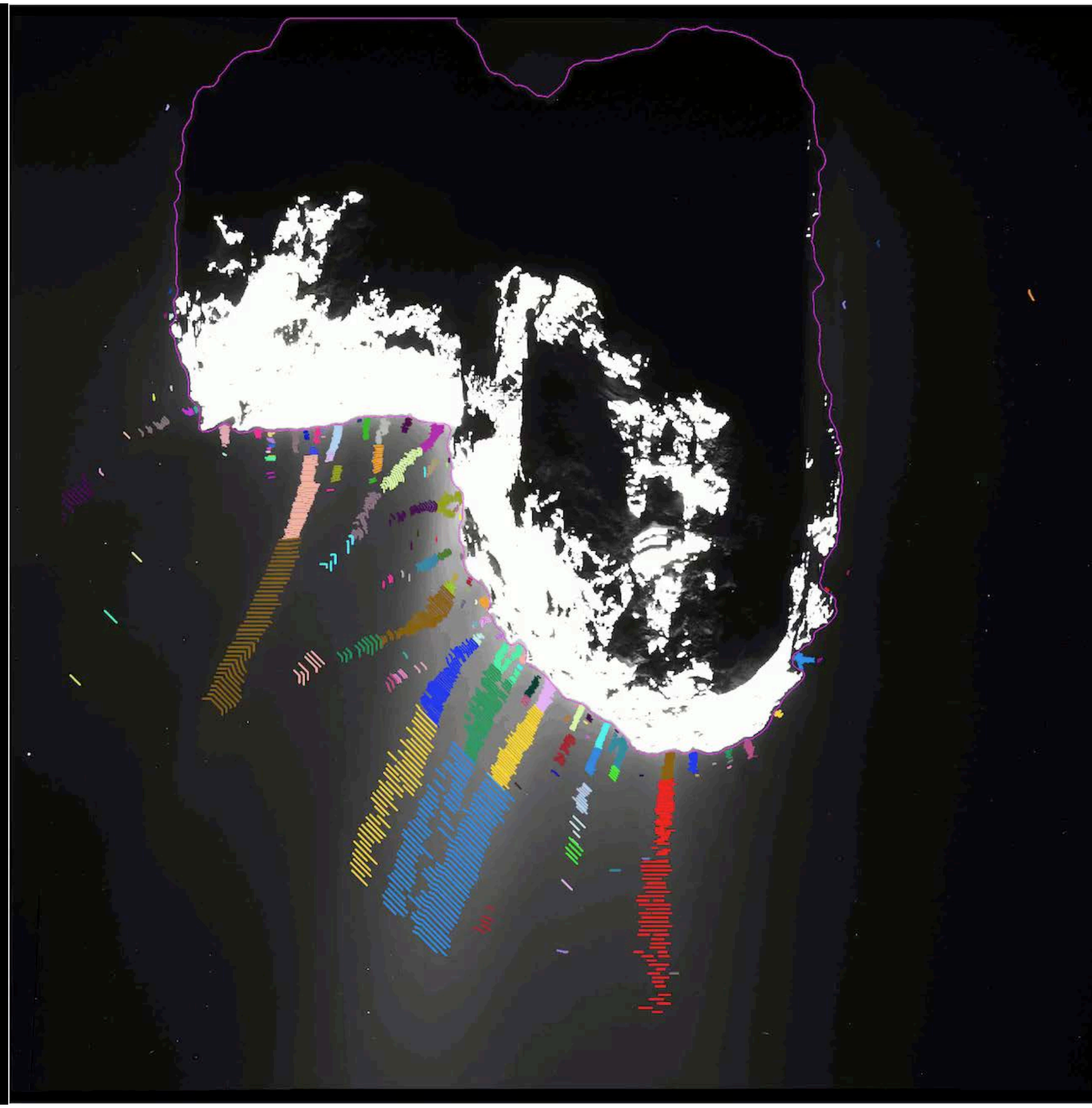


Plume Detection Rosetta OSIRIS

Brown et al. 2019 Astronomical J.

Collaboration w. H. Sierks/MPI

Original Image sequence credit:
OSIRIS/MPI, Rosetta/ESA



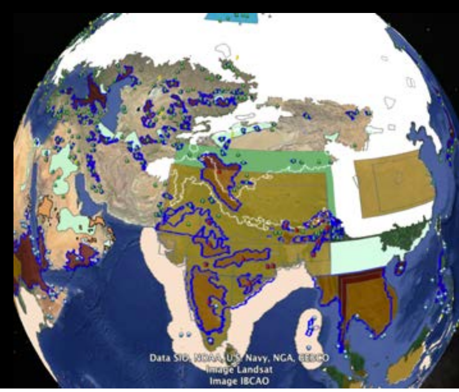
Coverage Scheduling

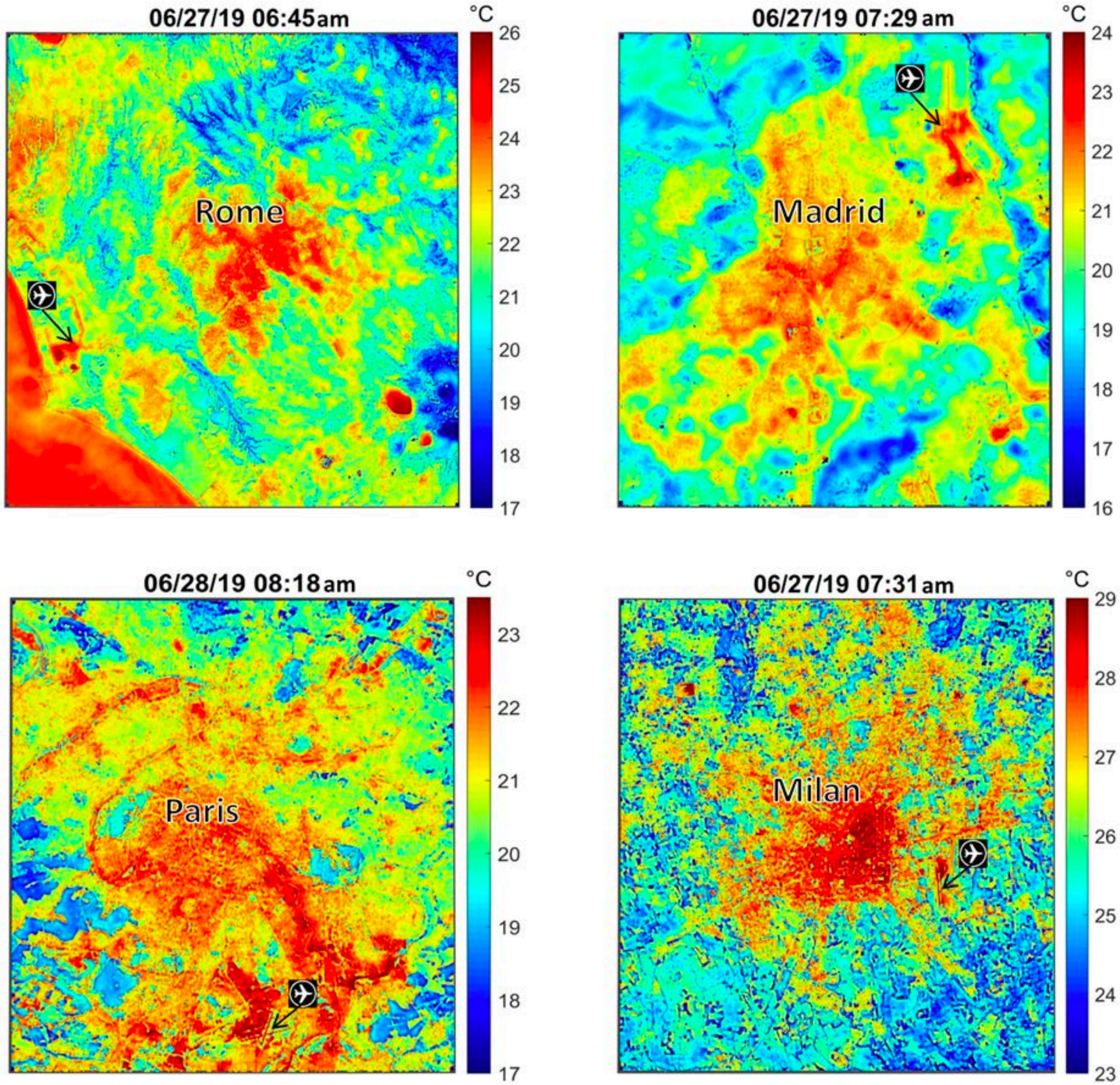
- Numerous missions involve variations of coverage scheduling, this technology is mature an in use for several NASA missions
  - ECOSTRESS: coverage, illumination, priority and background mapping, radiation keepouts, data management
  - OCO-3: visibility, illumination, complex geometry, area map prioritization, PMA calibration, complex rapid pointing and flip constraints
  - NISAR: data volume, power/energy, complex coverage campaigns

ECOSTRESS

OCO-3

NISAR

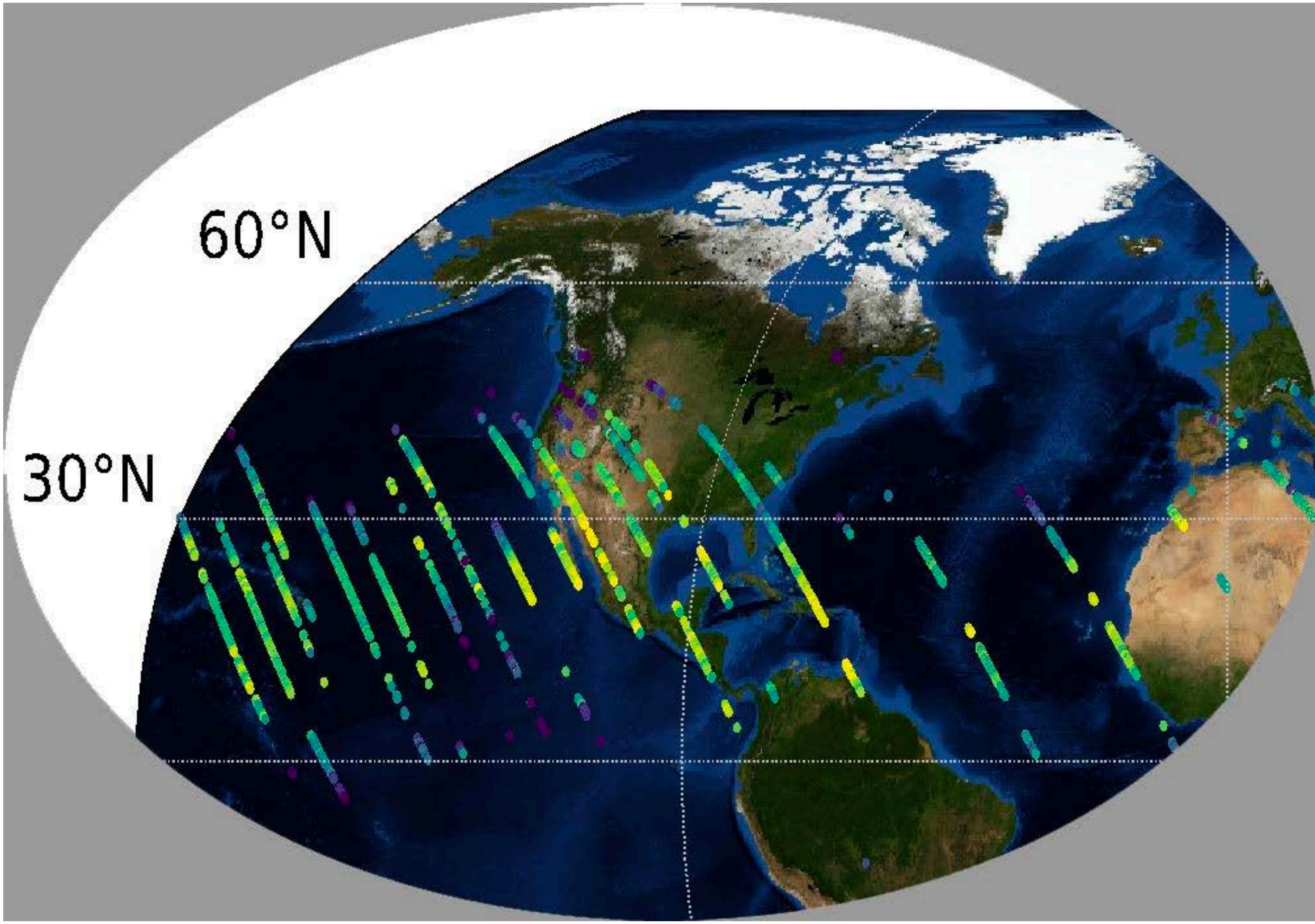




NEWS | JULY 2, 2019

NASA's ECOSTRESS Maps European Heat Wave From Space

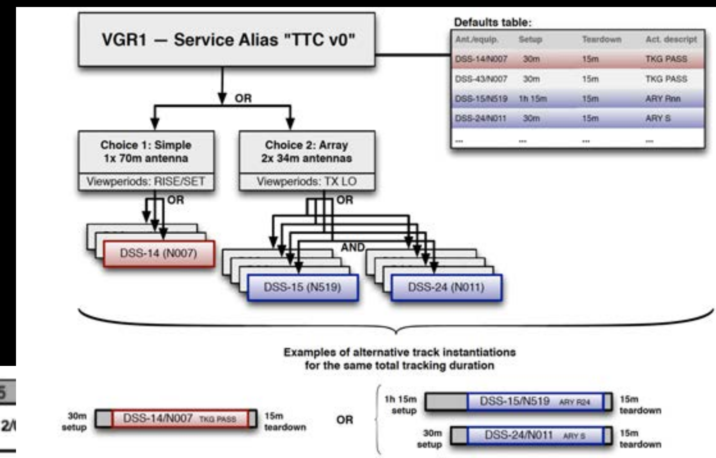
https://www.jpl.nasa.gov/news/news.php?feature=7445



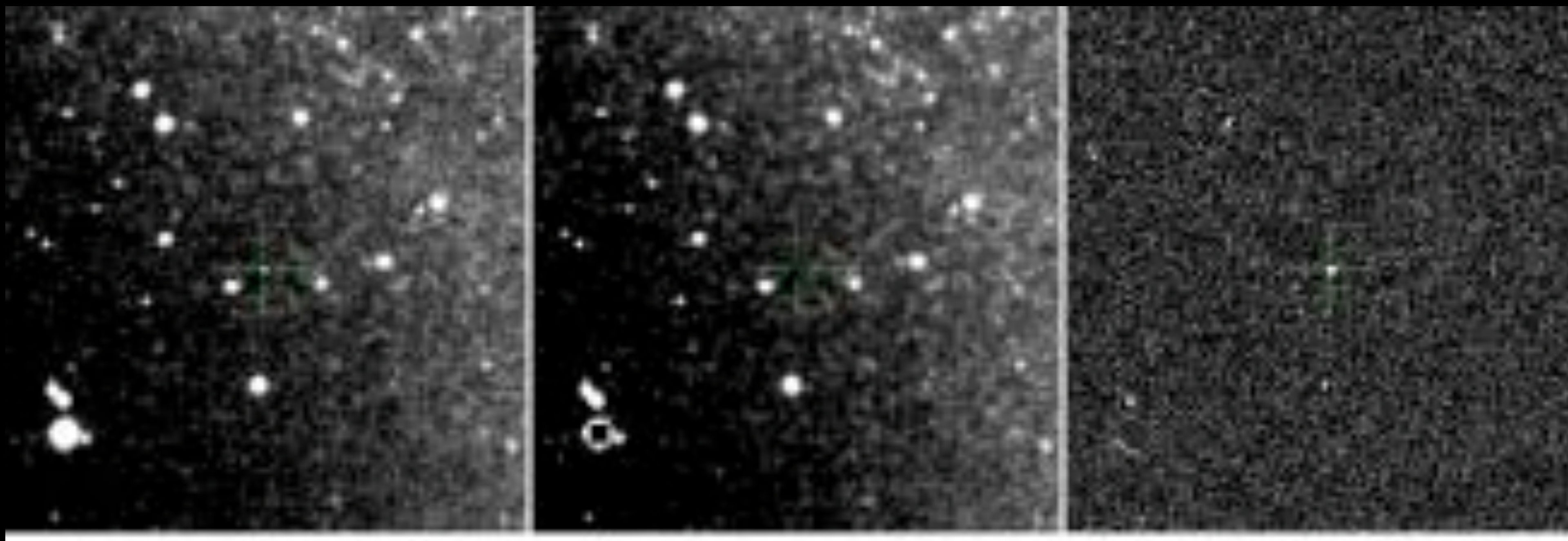
NEWS | JULY 12, 2019
NASA's Orbiting Carbon Observatory-3 Gets First Data

https://www.jpl.nasa.gov/news/news.php?feature=7452

No time for…ask me about…

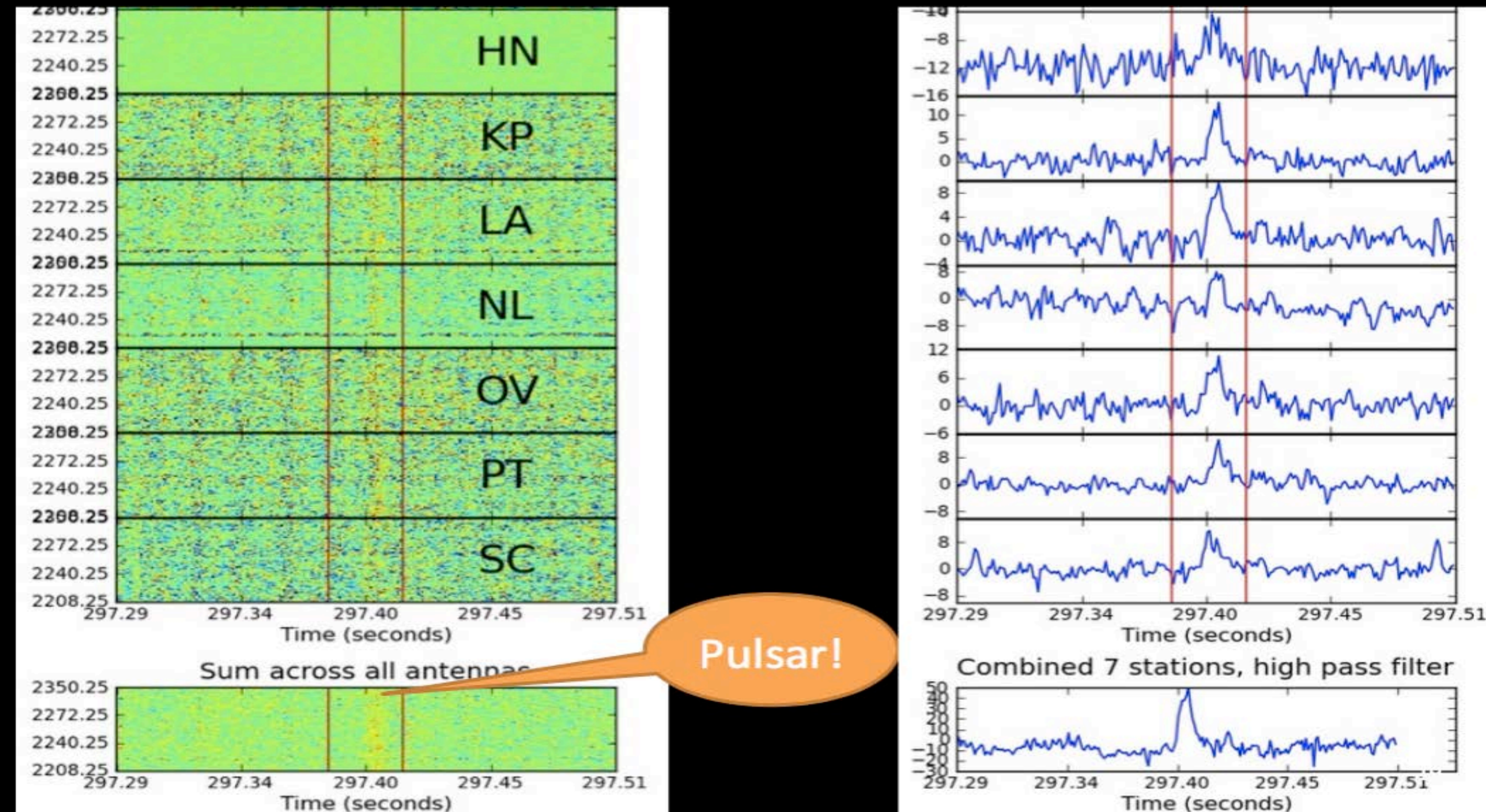


Constraint based scheduling for NASA's Deep Space Network
Demand forecasting [SpaceOps 2018], Midrange scheduling [AIMAG 2014], near real-time scheduling
Link complexity based scheduling [SpaceOps 2018]



Machine Learning for Automated Triage/detection of Visual Transient Events
Intermediate Palomar Transient Factory (i-PTF)
Continuous quality control and retraining
$10^3 \rightarrow 50$

Rebbapragada et al.

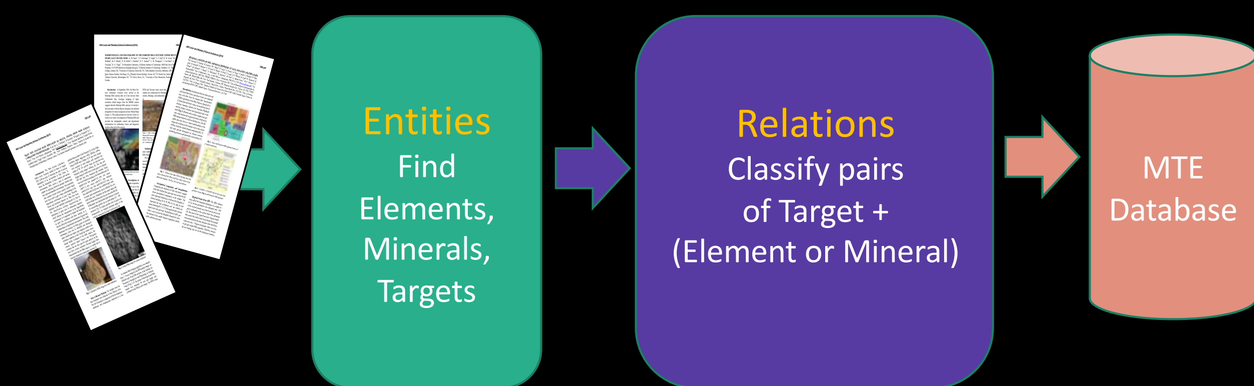


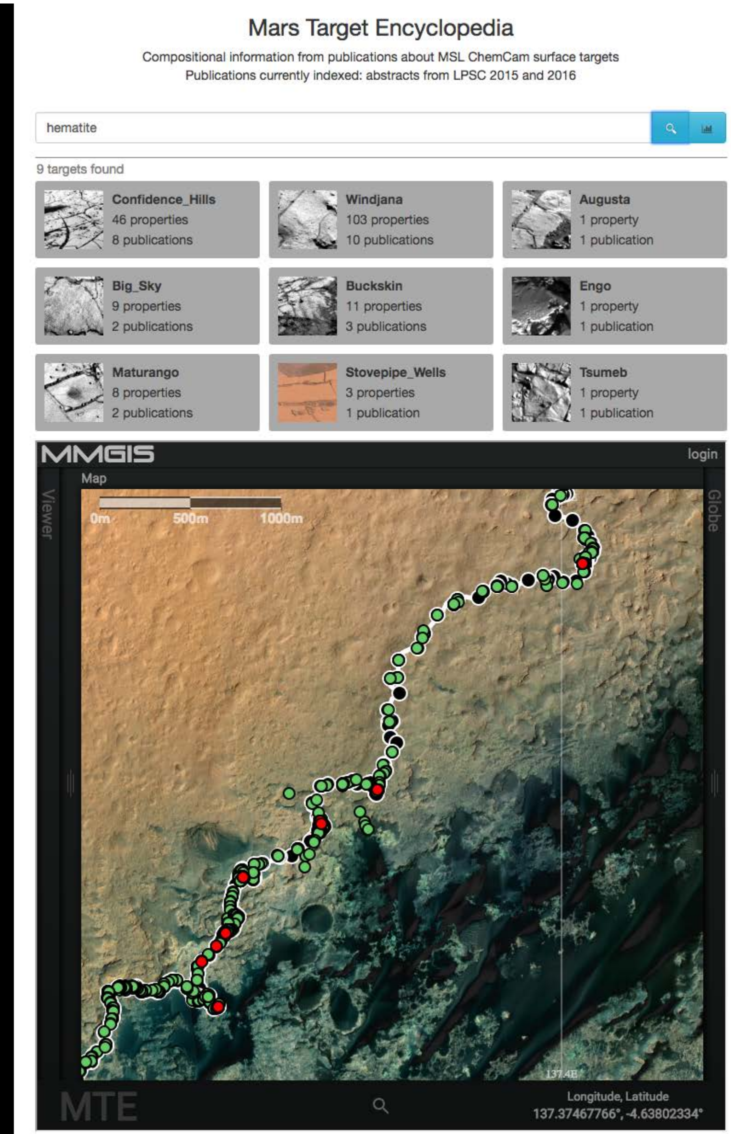
Machine Learning for Automated Triage/classification of Radio Transient Events
Very Long Baseline Array (VLBA)   Fast Transients Experiment (V-FASTR)
$10^5 \rightarrow$ 50 per 24h
Random Decision Forests, continuous quality control and retraining.

Wagstaff et al. 2016

Mars Target Encyclopedia

- Lunar and Planetary Science Conference
  - Three years
  - 5,920 documents
  - 2-page abstracts
  - 7.2M words

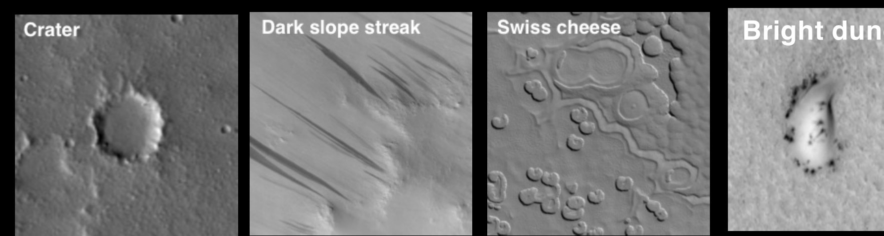




Wagstaff et al. 2018 IAAI

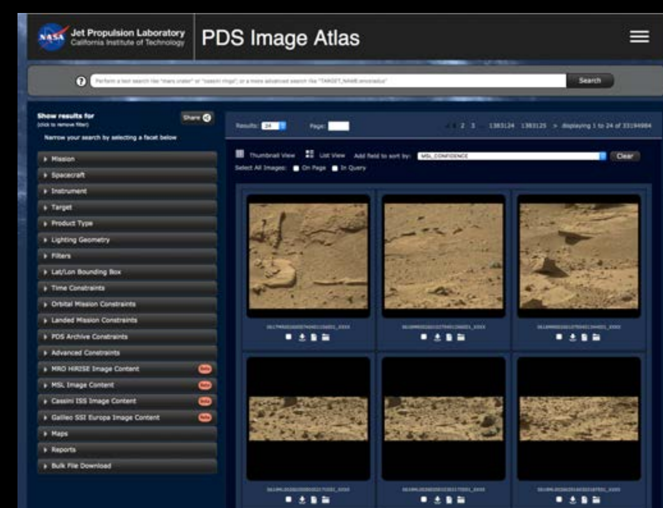
Deep Mars CNN Classification of Mars Imagery for the PDS Imaging Atlas

- MSL Rover data set[1]
  - 6,691 labeled images (Mastcam L/R eye, MAHLI)
  - 24 classes
- MRO HiRISE data set[2]
  - 10,433 labeled images
  - 8 classes
  - Augmentation: rotation, flipping, brightness adjustment



Example images for HiRISENet

Example images for MSLNet

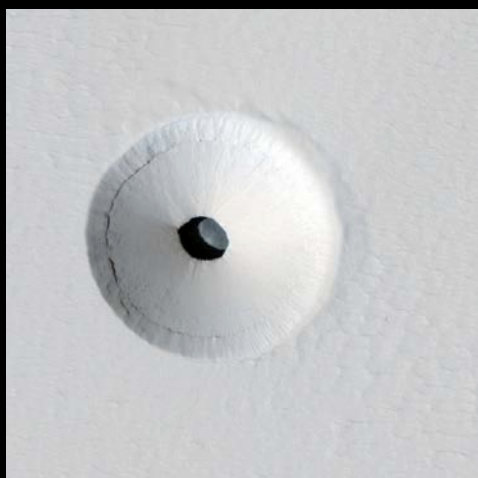


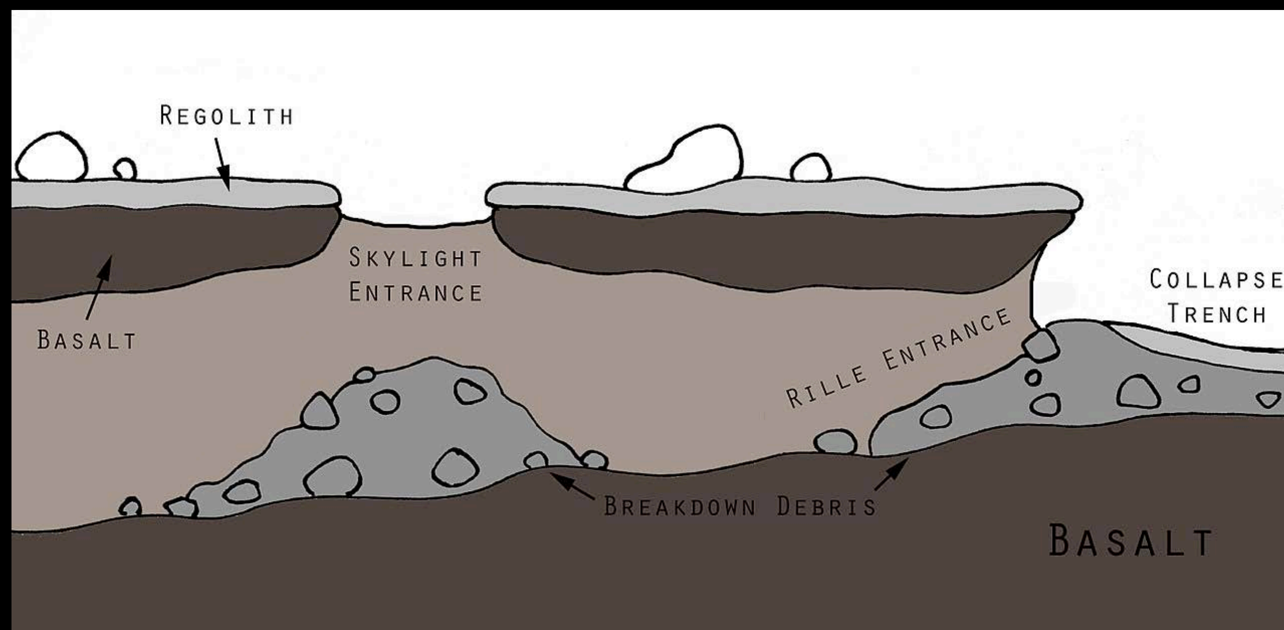
Result: Content indexing for PDS Atlas

Wagstaff et al. 2018a IAAI

Vaquero et al. 2018 ICAPS PlanRob

Cave Exploration





Artists concept.

Predecisional, for planning and discussion only.

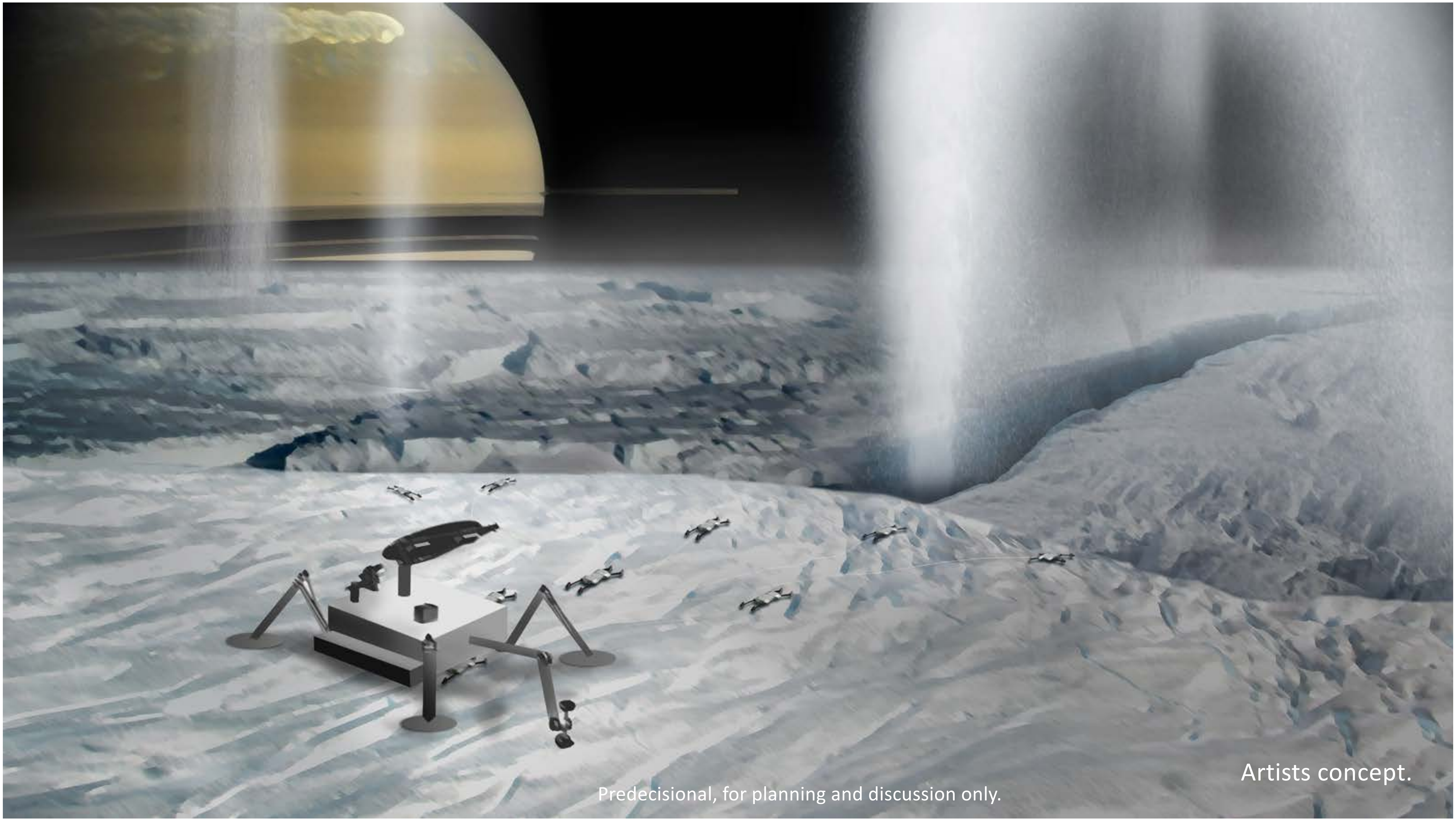
Rovers exploring Cave may depend on batteries for power → mission duration of days

- With such a short mission, rovers cannot wait for instructions from Earth
- True “Fire and forget” mission, completely autonomous

Dynamic Zonal Allocation Algorithm

- Each rover maps a pre-assigned zone of the cave
- Rovers deep into the cave must expend more energy driving
- Rovers closer to the cave entrance expend more energy relaying data from deeper rovers to the cave entrance
- Algorithm robust to loss of rovers – adjacent rovers shift to cover newly uncovered area
- Algorithm extends to “sneakernet” driving to cover areas beyond communications range

Visualization.


Artists concept.
Predecisional, for planning and discussion only.

NEO 100 Concept
Economically Assay 100 Near Earth Objects

Predecisional, for planning and discussion only.

Artists concept.

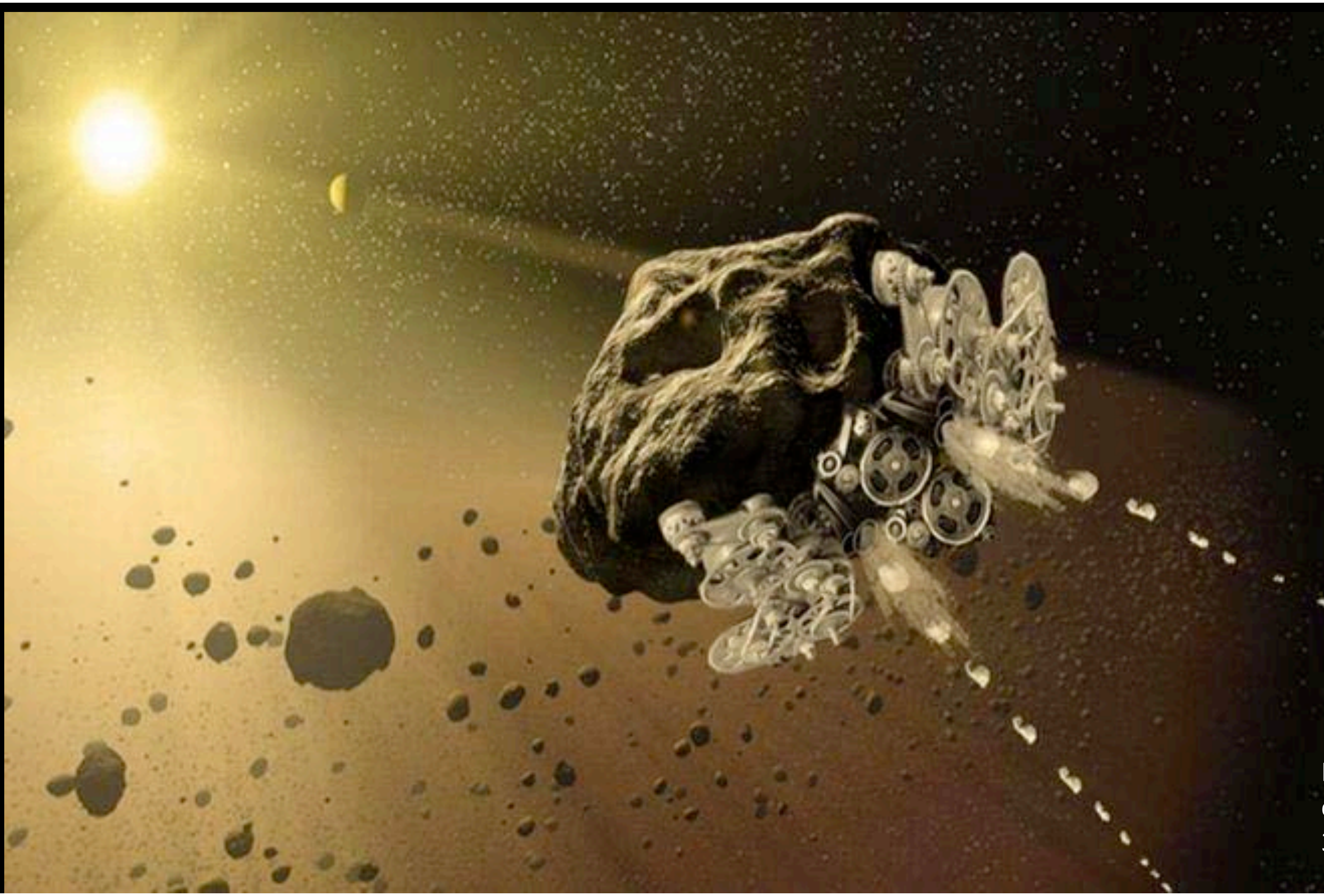


Image courtesy 3dprint.com

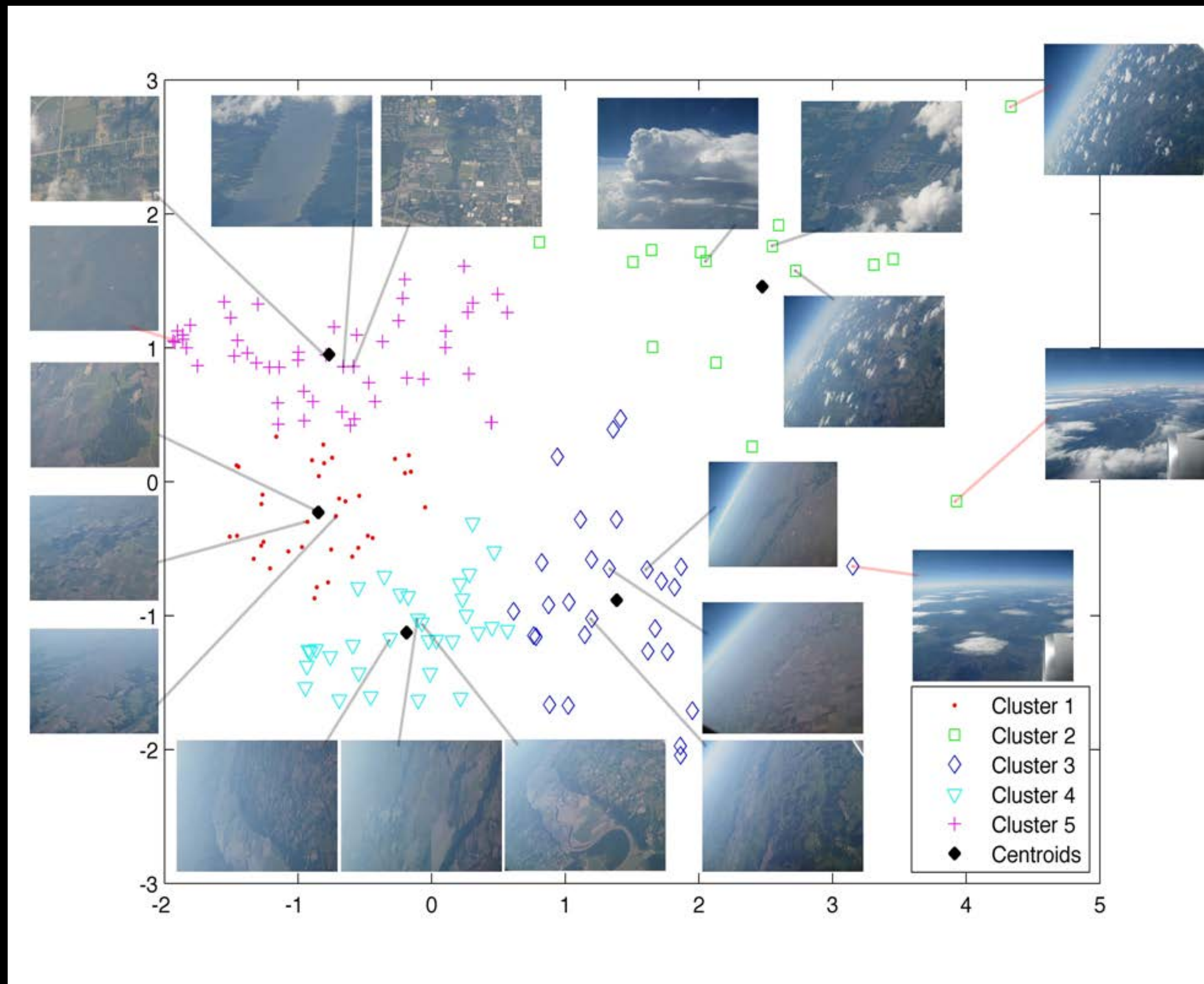
Lewis and Clark 1804-1806

mountains

rivers

lake

wildlife



Clustering and Metric Learning of Aerial Imagery [Hayden et al. 2012 ACM TIST]

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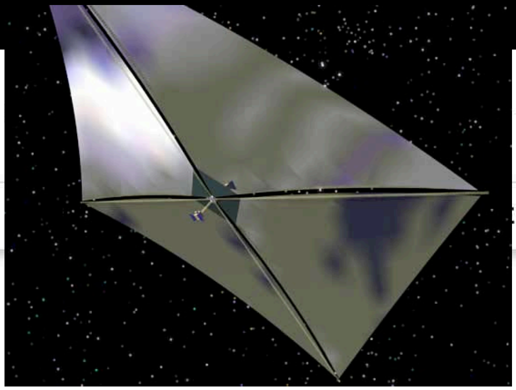


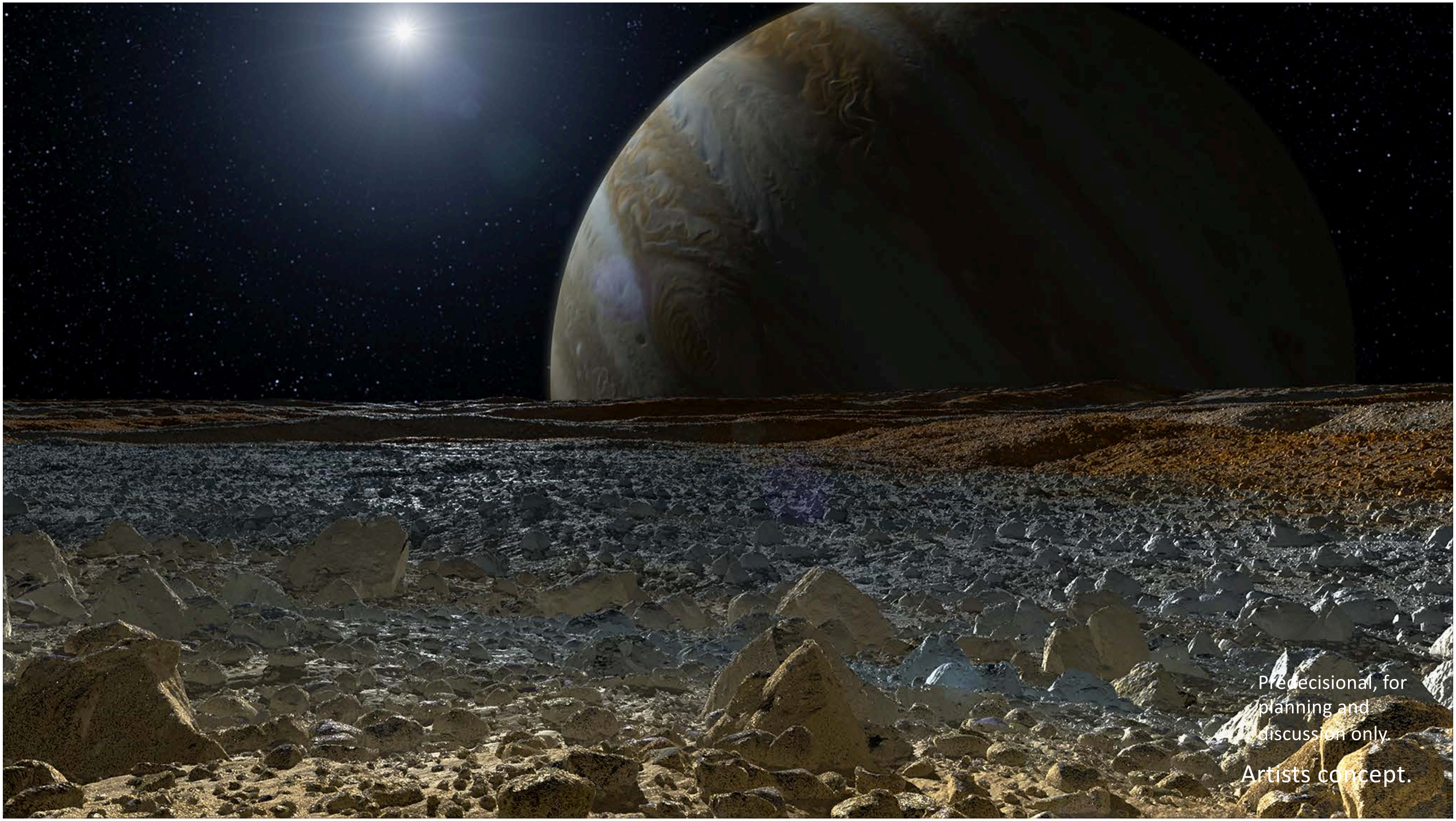
LATEST

ENGINEERING

How NASA's Search for ET Relies on Advanced AI

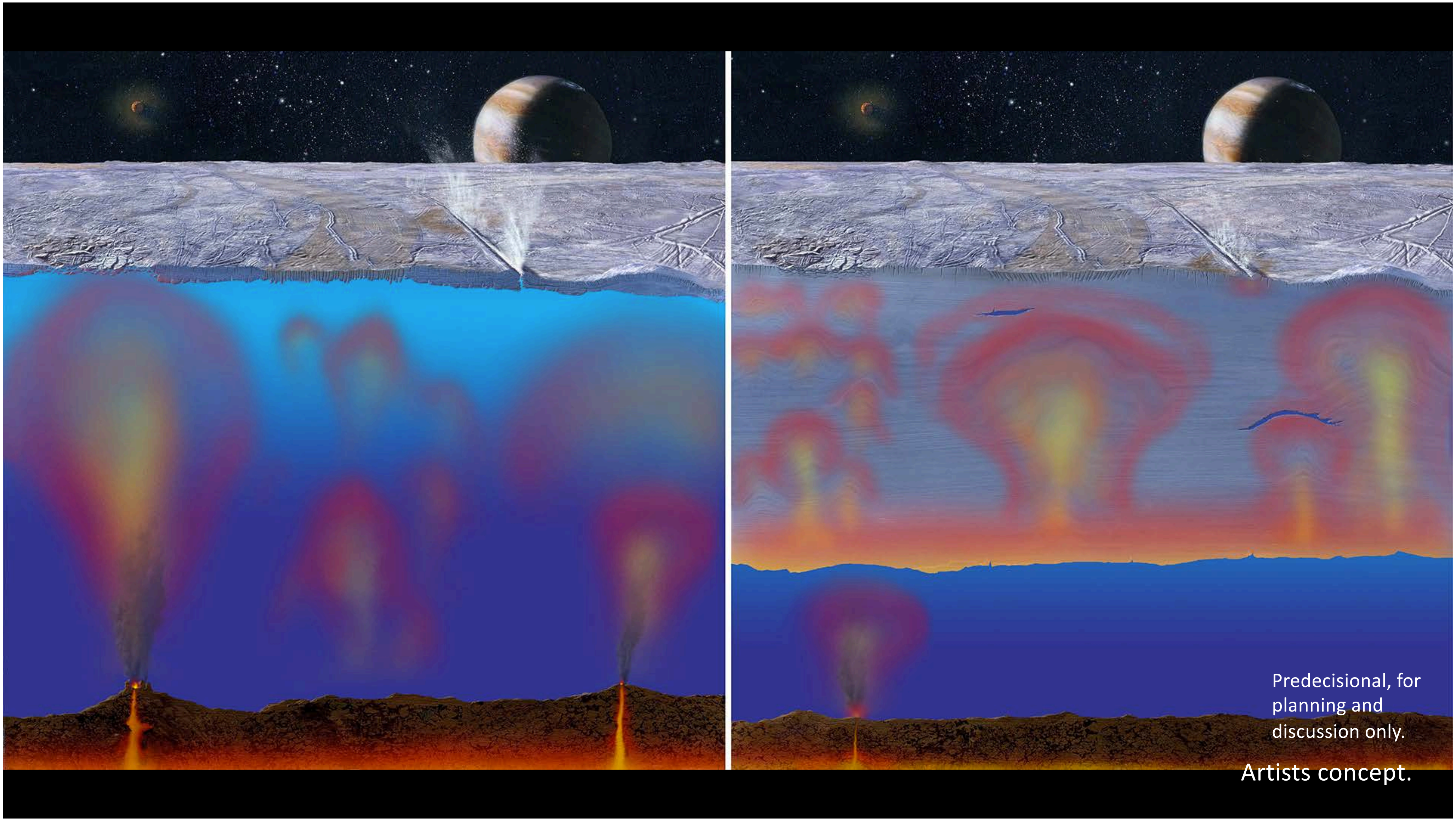
Jet Propulsion Laboratory's artificial intelligence chief describes the "ultimate" test for AI in space exploration

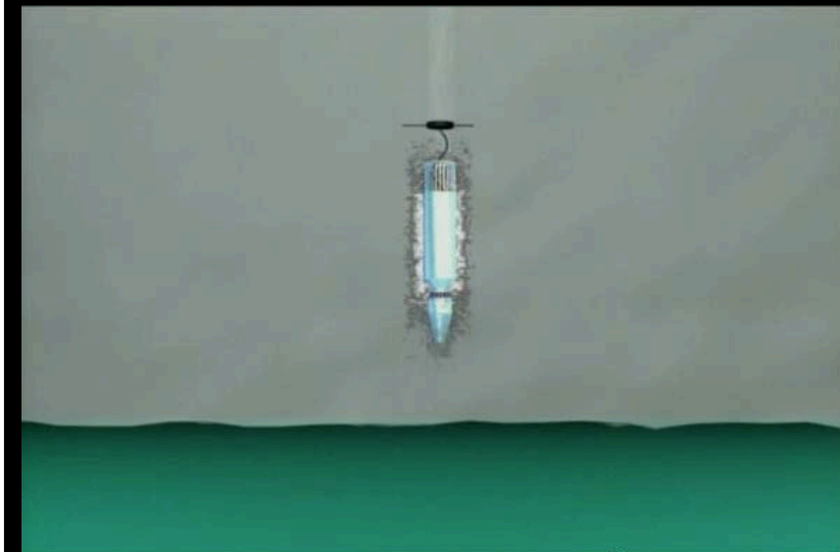
By Larry Greenemeier on December 28, 2017


Predecisional, for planning and discussion only.
Artists concept.

Predecisional, for planning and discussion only.

Artists concept.


Predecisional, for planning and discussion only.
Artists concept.



- A Europa Submersible would have spend a year or even more to penetrate kilometers of ice
- Then explore autonomously for weeks to months at a time searching for life, perhaps at hydrothermal vents
- A true challenge for AI!

Predecisional, for planning and discussion only.

Ocean Worlds submersible concept.

Deployment May 2017 (KISS)

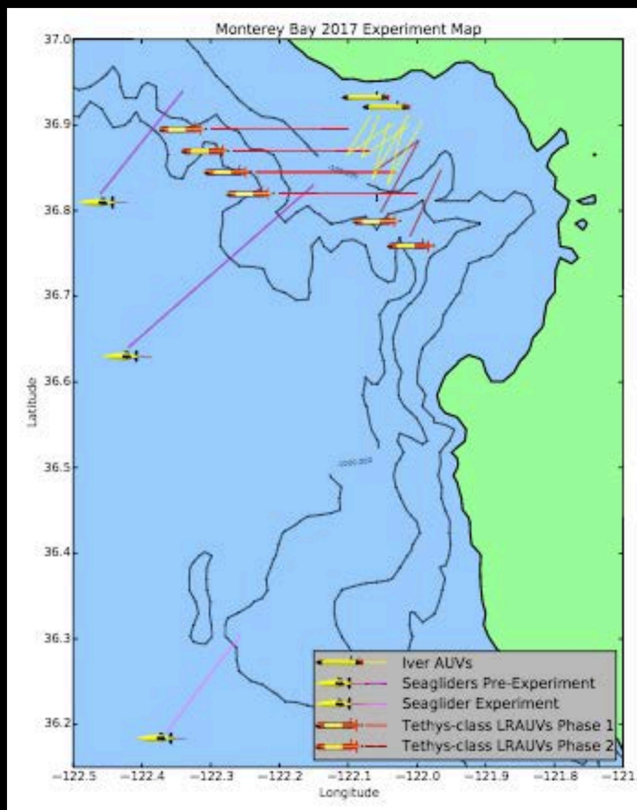
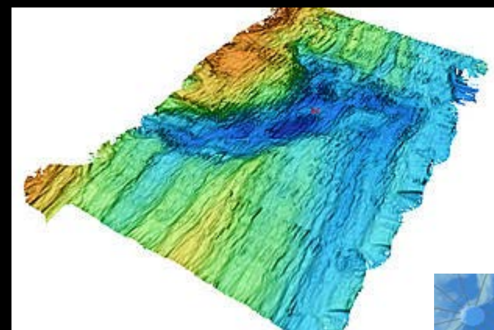


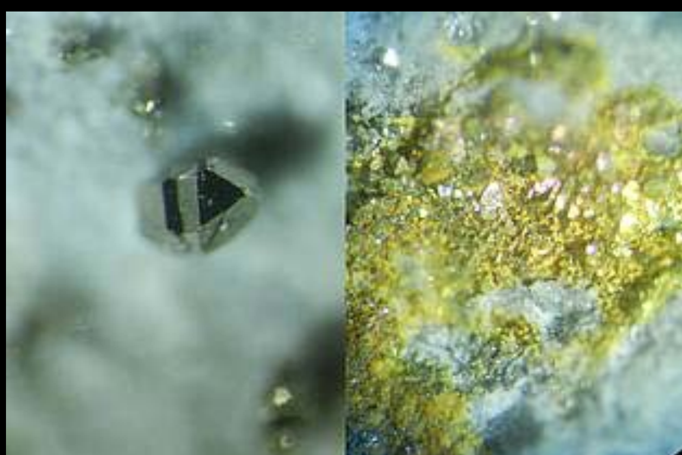
Figure 7: Kongsberg Underwater Technology, Inc. Seaglider onboard the R/V *Paragon*

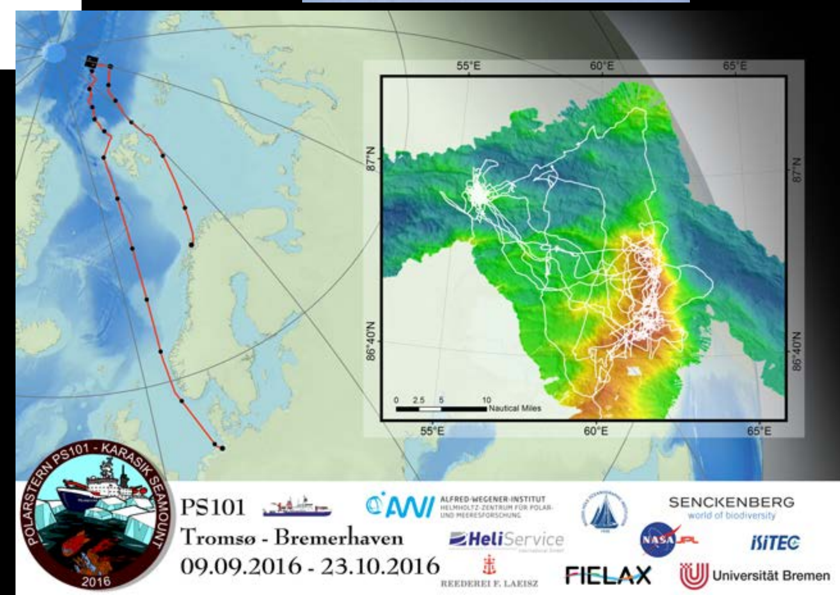
Figure 6: OceanServer Technology, Inc. Iver2 AUVs onboard the R/V *Shana Rae*

POC: A. Thompson / Caltech
S. Chien, A. Branch / JPL

From the Recent Polarstern Cruise, Karasik Massif 85 N

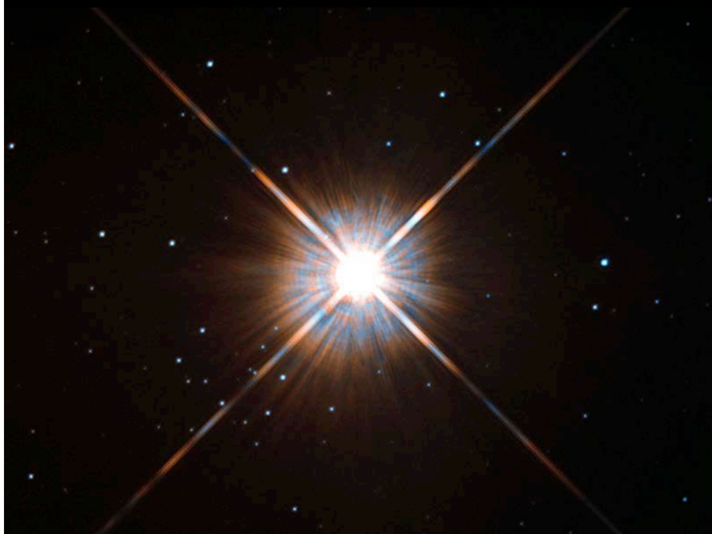


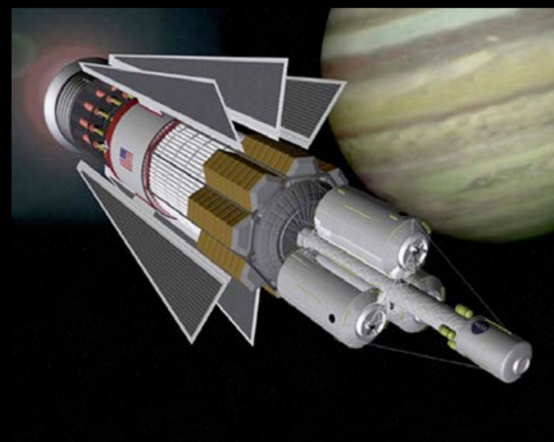


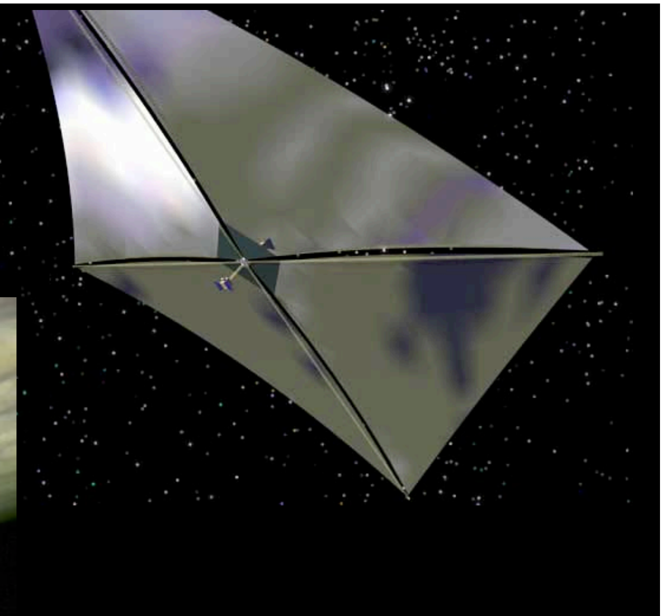


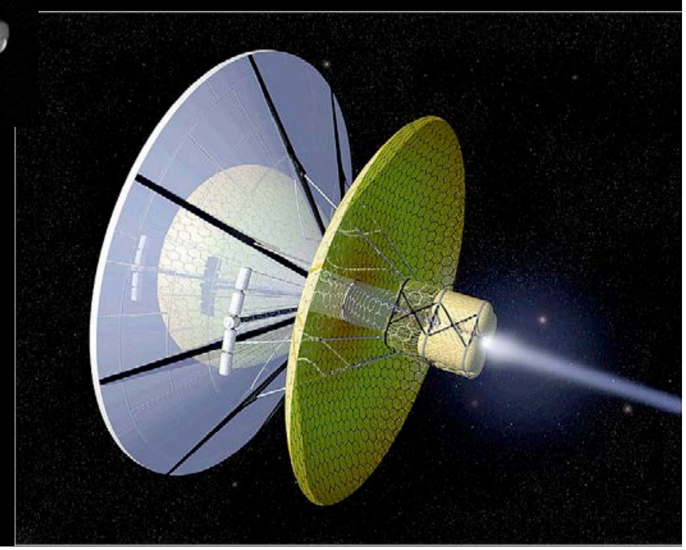
Images courtesy of A. Boetjius/AWI, C. German/WHOI, K. Hand/JPL

Interstellar Mission Concepts









Artists concepts.

Predecisional, for planning and discussion only.

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DARE MIGHTY THINGS

Jet Propulsion Laboratory
California Institute of Technology